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UGT Ground Shock Data and Effects Technology Transfer
Phase 1—Feasibility Study

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Technical Report

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13. ABSTRACT (Maximum 200 words)

This effort was a brief feasibility study directed toward determining whether ground motion and structural response data developed at the Nevada Test Site during the Defense Nuclear Agency underground nuclear test (UGT) program might be useful to the earthquake engineering community.

Response spectra were computed for ground motions from four UGT events. They were compared with response spectra from selected records from the Northridge Earthquake and with predicted spectra for various earthquake magnitudes and ranges. The general approach was to attempt to find an equivalence, based on spectral psuedo-velocity, between the earthquake and UGT ground motions. The general shapes of both types of spectra are comparable, but earthquake spectral velocities peak at significantly higher natural periods.

A UGT response spectrum for an estimated tunnel damage threshold range was compared with spectra from selected earthquake records made on soil and rock. It was concluded that one can probably make a good case that the spectral velocities and accelerations caused by earthquakes at typical depths for tunnels in rock will be significantly less than those associated with the tunnel damage threshold for the UGT events that were considered. However, the same case cannot be made for spectral displacements. Recommendations for addressing some remaining questions are included.

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PREFACE

This work was funded by the Defense Nuclear Agency (DNA) and was performed under a subcontract to Bechtel Nevada Corporation (Purchase Order No. 3957). The Technical Monitor was Mr. Sheldon Murphy. Support and advice were provided by Ms. Barbara Harris-West, Mr. Lawrence Gabriel, and Dr. George Baladi of DNA. The authors wish to thank all of these individuals.

We also wish to thank (1) Mr. Robert Bass for locating and evaluating all of the UGT ground motion records used in this program and for his advice on the conduct of the program, (2) Mr. Joseph LaComb for his advice and for reviewing and providing constructive comments on the results of our work, and (3) Mr. Carl Smith and Mr. Douglas Garbin of Sandia National Laboratory and Mr. Fred App of Los Alamos National Laboratory for providing ground motion data.

The FCDNA Test Operations Directorate would like to thank (1) Donald E. Yule, of the Earthquake Engineering and Geosciences Division, Geotechnical Laboratory, (2) Dr. Howard G. White, of the Geomechanics and Explosion Effects Division, Structures Laboratory, and (3) Dr. M. E. Hynes, Chief, Earthquake Engineering and Geosciences Division, Geotechnical Laboratory, for their thorough review of this report.

FORWARD

The general purpose of this report was to identify and document technology transfer opportunities to the private sector in the field of earthquake engineering based on ground motion data collected during research conducted by Defense Nuclear Agency underground nuclear test (UGT) program. Specifically, the authors had two objectives (1) characterizing the ground shock ground motion and their effects on underground facilities directed at improving similar cause and effect relations for earthquake induced motions and to (2) develop a case to support a decision for additional research into using ground shock data to further knowledge in source characterization, wave propagation, and constitutive behavior to improve prediction of earthquake induced ground motions and structural response. The approach was to first compile and evaluate free-field and surface UGT ground motion data. This data set was then compared to recorded earthquake data based on amplitudes, durations, and response spectra. The third step was to correlate these ground motion parameters with observed effects on tunnels and compare results with simplified procedures used in earthquake engineering for estimating similar structural response.

In this report, the author immediately presents an important fundamental distinction between UGT and earthquake ground motions. The UGT ground motions have durations of less than 1 second and are predominantly compression type waves in contrast to earthquake ground motions which have durations measured in seconds and whose energy is mostly contained in shear waves. The comparison between these two data sets were based on their respective response spectra which is a useful and common tool when investigating structural response due to ground motions. A procedure is briefly described for developing synthetic ground motions below the ground surface from surface motion spectra. This procedure is based on random vibration theory using a target spectra and existing earthquake time histories as input to develop a new time history which matches the target spectrum. This "matched" time history is then deconvolved down to a depth of interest using a one dimensional wave propagation numerical procedure and a site-specific constitutive model. Tunnel response due to shaking was discussed for the cases of axial and curvature deformations and ovaling or racking deformations. This response is based on the assumption that tunnel strains will be equal to free field strains and that these strains will be a function of peak particle velocity and propagation velocity of the wave field. This relation between propagation velocity and strains was used to concentrate on comparing these two ground motion data sets using spectral velocity.

Four UGT events were selected from which 28 free field records were selected for this study. The peak acceleration limit for record selection was 250 g's which is much greater than nominal earthquake peak levels of less than 1 g. An extensive set of earthquake data was evaluated from the Landers and Northridge earthquakes, approximately 500 records. The comparison of these two data sets reveals that the earthquake ground motion amplitudes have much lower peak spectral velocities than found in the UGT data. Response spectra were generated from empirical based attenuation relations developed for western US earthquakes, (Boore et al, 1994). This procedure enabled deriving a data set of ground motion predictions for large magnitude events at

close ranges that might provide a more favorable data set for comparison with the ground shock data. The actual earthquake data used in the comparison with UGT data were from multistory building upper floors or roofs. The spectral velocities for UGT records show that the peak velocity range from 0.08 to 0.25 sec periods which is well below the 1.0 second or greater periods for earthquakes. Radial UGT data was compared to non-radial data and surface data to see if non-radial data would have characteristics more comparable to earthquake data. The rationale was to find UGT data that might contain more shear waves. Although the non-radial data had peak velocities at lower periods than the radial data, it was not a significant difference and comparison to earthquake data was not improved. Due to the large difference in the duration of strong motion shaking between earthquake and UGT time histories, the influence of length of record on the calculated response spectra was investigated. It was determined that if a partial record was extracted which contained several cycles around the peak acceleration its response spectra reasonably matched the response spectra calculated from the entire record. Based on this result, the authors concluded that UGT data should not be excluded for use in earthquake engineering analyses because of the short duration of the records. Another finding from the comparison of the earthquake and UGT data was that the shapes of response spectra are similar, although the UGT spectra is somewhat broader. The conclusion from comparing velocity spectra of UGT with the earthquake data was that they differed dramatically in amplitude and period content. The UGT data is from a rapid volume expansion source phenomena (predominately high frequency compression waves) in contrast to earthquake ground motions from a predominately shearing deformation source of much longer duration (predominately low frequency shear waves). Furthermore, additional efforts would not be productive to show that UGT and earthquake ground motions data are similar.

The report then proceeded to present research on tunnel response to UGT ground motions. The tunnel response analysis was investigated by finding the maximum range for significant damage and then comparing the UGT response spectra with earthquake spectra for this limiting range. From the five UGT events studied the maximum range was approximately 660 ft. The criteria for selection of earthquake data was records with high amplitude peak velocities. Comparison of this high velocity earthquake data with the UGT response spectra data at the limiting range supports anecdotal data that underground structures are not at great risk due to earthquake shaking. This follows from the fact that earthquake ground motions have spectral velocities much lower than produced by UGT which produced tunnel damage.

Finally, the report concluded with recommendations for follow on research based on the findings from this feasibility study. These recommendations addressed earthquake data evaluation of tunnel damage data for correlation with UGT data, analytical studies of tunnel response to ground motions, and a seismological investigation to characterize the UGT Wakefield in more detail than response spectra.

The authors provide ample evidence that UGT ground motion data is predominately compression waves at frequencies much higher than surface and shear wave dominated earthquake ground motion data. The UGT data set is also mostly at near field stations and have very high spectral amplitudes compared with earthquake data. The authors did a commendable job in attempting to locate or derive earthquake response spectra data that is comparable to high frequency, high

amplitude UGT ground motion data (prediction equations for near field, high magnitude, soils with low propagation velocities, and earthquake records from upper stories of building). They were somewhat successful in matching amplitude but not frequency content. This dramatic difference in frequency content and wave type composition is a critical impediment in continuing work along these lines. The authors reach the same conclusions and do not recommend continuing with the next phase.

We are, therefore, publishing this report and making it available to the general public because this report quantifies and documents the differences in the UGT ground shock data and the earthquake data sets.

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CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement

To Convert From	To	Multiply
angstrom	meters (m)	1.000 000 X E–10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E+2
bara	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E–28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermocemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E–2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E–2
degree Fahrenheit	degree kelvin (K)	^{t}K=(t^{o}f + 459.67)/1.8
electron volt	joule (J)	1.602 19 X E–19
erg	joule (J)	1.000 000 X E–7
erg/second	watt (W)	1.000 000 X E–7
foot	meter (m)	3.048 000 X E–1
foot–pound–force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E–3
inch	meter (m)	2.540 000 X E–2
jerk	joule (J)	1.000 000 X E+9
joule/kilogram (J/Kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton–second/m^2 (N–s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E–6
mil	meter (m)	2.540 000 X E–5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E–2
pound–force (lbf avoirdupois)	newton (N)	4.448 222
pound–force inch	newton–meter (N•m)	1.129 848 X E–1
pound–force/inch	newton/meter (N/m)	1.751 268 X E+2
pound–force/foot^2	kilo pascal (kPa)	4.788 026 X E–2
pound–force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound–mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E–1
pound–mass–foot^2 (moment of inertia)	kilogram–meter^2 (kg•m^2)	4.214 011 X E–2
pound–mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E–2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E–4
shake	second (s)	1.000 000 X E–8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg,0^{0}C)	kilo pascal (kPa)	1.333 22 X E–1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation

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SECTION 1

INTRODUCTION

This report documents work performed during an approximately eight-month program in support of the Department of Defense's (DoD) Technology Transfer Program. In general, this is a program intended to transfer technology that was developed during the conduct of various DoD programs to civilian industry. Specifically, the effort reported herein was directed toward determining whether ground motion and structural response data developed at the Nevada Test Site during the Defense Nuclear Agency (DNA) underground nuclear test (UGT) program might be useful to the earthquake engineering community.

1.1 SCOPE AND OBJECTIVES.

The investigation of the transfer of UGT data to the earthquake engineering community was considered by all of those involved to be a two-phase program. The first phase, which is described in this report, was to be conducted as a feasibility study that would support a decision about whether a more extensive second phase program was warranted.

The program was founded on the belief that the ground shock data developed during the UGT program might be useful to the earthquake engineering community in two distinct ways. First, information on the relationship between ground motion characteristics and their effects on underground facilities (tunnels, equipment, etc.) might be relevant to developing procedures to predict the effects of earthquake ground motions on tunnels and equipment. Second, the ground motion recordings themselves might have special features (such as known source functions and material properties, redundancy, large ground motion levels, and coverage of both surface and subsurface locations) that are not available in earthquake recordings and might therefore be useful for developing and testing methods for predicting strong ground motions from earthquakes. The Phase I program addressed only the first of these.

A small number of UGT events were selected for consideration. The two primary selection criteria were (1) readily accessible ground motion data and (2) availability of response data. Three activities were conducted during Phase I. The first was to

compile and evaluate free-field and surface ground motion recordings from the files of Mr. Robert C. Bass and the Sandia and Los Alamos National laboratories. The second was to identify and characterize the engineering characteristics (amplitudes, durations, and response spectra) of the ground motions and to compare them with those of earthquake recordings. The third activity was to correlate the information on ground motion characteristics with the observed effects on tunnels and evaluate the efficacy of simple procedures commonly used in earthquake engineering (e.g., the use of response spectra) to relate these effects to input ground motions. Our general approach to these activities is discussed in Section 2.

The specific objectives of the Phase I program were as follows:

- Develop relationships between tunnel behavior and response spectra for ground motions from UGTs that will contribute to the seismic design of tunnel support systems.

- Develop information that would support a decision about whether Phase II of the program is warranted.

1.2 REPORT ORGANIZATION.

The general approach that was followed while accomplishing this effort is described in Section 2, along with brief discussions of response spectra and tunnel response parameters. The results of several activities that were accomplished prior to attempting to correlate ground motions with tunnel response are described in Section 3. In Section 4, assessments of tunnel damage and comparisons of a UGT response spectrum (for a measurement at the damage threshold) with appropriate earthquake spectra are described. Recommendations are presented in Section 5.

SECTION 2

GENERAL APPROACH

Our general approach was to compare ground motions from UGTs with those from earthquakes. Two primary characteristics of UGT free-field motions that are recorded at underground locations are (1) they are primarily dilatational waves and (2) they are relatively short in duration (fractions of a second). On the other hand, the majority of the energy in most earthquake motions is contained in the shear wave component and these waves have durations measured in seconds. Our approach was to compare the two types of records on the basis of response spectra.

It is recognized that some readers of this report may not be familiar with the details of the precedures used in earthquake engineering. Therefore, brief discussions of response spectra and tunnel response parameters are presented in the following subsections. Section 2.3 contains a brief discussion of the working hypothesis underlying the Phase I work.

2.1 RESPONSE SPECTRA.

Response spectra have been used for many years to characterize input ground motions. Such characterizations allow different input motions to be distinguished on the basis of how they affect structural response. Generally, spectra are developed for the response of linear single-degree-of-freedom oscillators, although they may also be developed for nonlinear systems. The derivation of response spectra may be found in standard works on structural dynamics, such as (Blume, 1961) and (Paz, 1991).

Briefly stated, a response spectrum is a plot of the maximum response (displacement, velocity, or acceleration) of a single-degree-of-freedom oscillator to a particular load function for all possible natural periods (or frequencies). Spectra may be developed for specific percentages of critical damping.

The load function for spectra developed for use in earthquake engineering is normally taken to be a base excitation equal to the ground motion caused by an earthquake. The responses of interest, then, are:

- the displacement of the mass of the oscillator relative to its base

- the velocity of the mass of the oscillator relative to its base
- the absolute acceleration of the mass of the oscillator

A spectral plot for each maximum response may be prepared. However, it is possible and more convenient to plot all three maximum responses on a single chart using logarithmic scales. In order to do so it is necessary to replace the maximum values of acceleration and velocity with two approxomate quantities: the pseudo-acceleration S_a and the pseudo-velocity S_v. The maximum relative displacement will be designated by the letter S. These three quantities (S, S_v, and S_a) are referred to in this report as the spectral displacement, the spectral velocity, and the spectral acceleration, respectively. The relationships among them are given by

$$S_v = wS = 2pfS$$

$$S_a = w^2S = 4p^2f^2S$$

where f is the natural frequency and w is the circular frequency (w = 2pf).

According to (Blume, 1961):

> The ... spectral acceleration is actually the maximum acceleration for a system without damping, and is very nearly equal to the maximum acceleration for a system with damping.
>
> The [spectral velocity] is also very nearly equal to the maximum relative velocity except for very low frequency systems. It is precisely equal to the maximum velocity if the latter occurs after the ground motion ceases. It is a measure of the elastic energy in the spring elements of the system.

In the earthquake engineering community, response spectra associated with motions at the ground surface are estimated for particular distances from the sources of earthquakes of particular magnitudes. These spectra are used to develop coefficients that are incorporated into building codes and used in the design of surface structures such as buildings.

A surface motion spectrum may also be used to define ground motion conditions for use in the design of underground structures. This is done by developing a hypothetical acceleration time history that will cause the estimated surface motion response

spectrum (e.g., by using the RASCAL code (Silva, 1987) to modify a real earthquake time history). The hypothetical surface time history is then deconvolved to the depth of interest, thereby defining the design environment for an underground structure such as a tunnel. The deconvolution may be performed using the SHAKE code (Idriss, 1992).

2.2 TUNNEL RESPONSE.

The response of tunnels to relatively-low-level ground shaking (such as earthquake-induced motions) may be divided into two categories:

- The effects due to axial and curvature deformations
- The effects due to ovaling (or racking) deformations

For unlined tunnels and those with flexible linings, one may assume that in both categories, tunnel strains will be approximately equal to the free-field strains. Equations for free field strains are presented in the following subsections.

2.2.1 Axial and Curvature Deformations.

The following equation for computing longitudinal strains in the liner of a horizontal tunnel (or in the soil or rock adjacent to the tunnel) due to the free-field deformations of a horizontally-propagating shear wave was developed by Newmark (Newmark, 1968).

$$\varepsilon_{ff} = \pm\frac{V_s}{C_s}\sin\theta\cos\theta \pm \frac{Ra_s}{C_s^{\ 2}}\cos^3\theta \qquad (2.1)$$

where V_S = peak particle velocity

C_S = effective shear wave propagation velocity

a_S = peak particle acceleration

R = tunnel radius

q = angle of incidence between the shear wave and the tunnel axis

The first term on the right side of Equation 2.1 is the strain due to longitudinal deformation (i.e., parallel to the tunnel axis). The second term is the bending strain due to curvature of the tunnel axis. The maximum value of the axial strain occurs when q is 45 degrees. The maximum bending strain (which occurs when q is zero) is generally much smaller than the maximum value of the axial strain because the shear-wave propagation velocity is squared in the denominator of the bending strain term.

Therefore, the maximum strain from a shear wave can be approximated by substituting q = 45 degrees in Equation 1. This yields

$$\varepsilon_{max} = \pm\frac{V_s}{2C_s} \pm 0.35\frac{Ra_s}{C_s^2} \tag{2.2}$$

The equation corresponding to Equation 2.1 for use with horizontally propagating dilatational waves (P-waves) is (St. John, 1985):

$$\varepsilon_{ff} = \pm\frac{V_p}{C_p}\cos^2\theta \pm \frac{Ra_p}{C_p^2}\sin\theta\cos^2\theta \tag{2.3}$$

where $C_p = \sqrt{\frac{2(1-\nu)}{(1-2\nu)}}C_s$ = dilatational wave propagation velocity

V_p = peak particle velocity

a_p = peak particle acceleration

Axial strain is maximized when q = 0. Again, the bending strain is generally much smaller than the axial strain, so the maximum strain can be estimated by

$$\varepsilon_{max} = \pm\frac{V_p}{C_p} \tag{2.4}$$

2.2.2. Ovaling Deformations.

Tunnels are also subject to the effects of ovaling (or racking) deformations, i.e., deformations in the plane of the cross section of the tunnel. Under the assumption that tunnel liners will conform to the free-field shearing strains in the planes of their cross sections, the following equation is provided by Wang (Wang, 1993), although derived by others. This equation may be used to estimate the maximum hoop strains in the tunnel walls.

$$\varepsilon_{total} = \frac{V_s}{C_s}\left\{3(1-\nu_m)\left(\frac{t}{R}\right) + \frac{1}{2}\left(\frac{R}{t}\right)\left[\frac{E_m(1-\nu_l^2)}{E_l(1+\nu_m)}\right]\right\} \tag{2.5}$$

where V_s = peak particle velocity

C_s = effective shear wave propagation velocity

R = tunnel radius

t = liner thickness

E_m = Young's modulus of the medium

ν_m = Poisson's ratio of the medium

E_l = Young's modulus of the tunnel lining

ν_l = Poisson's ratio of the tunnel lining

The first term in Equation 2.5 is the bending strain; the second term is the thrust strain.

2.3 WORKING HYPOTHESIS.

Damage to deep tunnels located in sound rock from earthquake-induced ground shaking has rarely been observed (e.g., Sharma, 1991). This is also generally true of tunnel response during DNA UGTs at ranges associated with ground motion levels that are normally of interest to the earthquake engineering community. On the other hand, there are examples of significant damage from earthquake-induced ground shaking to tunnel portals and to shallow tunnels located in soil. Our working hypothesis was as follows:

> If it can be demonstrated that there is a consistent relationship between the spectra for ground motions from UGTs and ground motions from earthquakes, then the UGT data may be useful in the seismic design and analysis of the support structures for tunnels (at least for tunnels in soil and for portal structures).

It is clear from Equations 2.1 through 2.5 that tunnel strains are theoretically a direct function of particle velocity. Because shear waves are predominant in earthquake ground motions, Equations 2.1, 2.2, and 2.5 are most important for earthquake response; Equations 2.3 and 2.4 are probably more important for the response to UGT ground motions at relatively low free-field stress levels.

It appears reasonable to postulate that tunnel response is correlated with spectral velocity, both for UGTs and earthquakes. Consequently, we decided that the appropriate approach was to attempt to find an equivalence, based on spectral velocity, between earthquake and UGT ground motions.

Evaluations of earthquake and UGT spectra are described in the next section. In both cases we dealt with the spectral response of linear single-degree-of-freedom oscillators. Also, we limited our study to the spectra associated with five percent of critical damping. Although the evaluation of earthquake and UGT spectra are discussed separately, they were done in parallel and interactively.

SECTION 3

EVALUATION OF RECORDS AND SPECTRA

Several "preliminary" activities that were carried out prior to attempting to correlate ground motions with tunnel response are described in this section. Some observations based on these preliminary activities are discussed in Section 3.9.

3.1 EVENT SELECTION AND IDENTIFICATION.

Four UGT events with comparable yields were selected for consideration during the Phase I effort. As stated in Section 1, the two primary selection criteria were (1) readily accessible ground motion data and (2) availability of response data. All of the events considered were horizontal line-of-sight tests conducted by DNA.

In order to avoid any requirement to classify the data or the results of the study, it was decided to assign code numbers to the UGT events. These numbers were assigned prior to selecting the specific events to be considered. Events 5, 6, 13, and 25 were selected, and all of the UGT data discussed herein are identified only by the appropriate event numbers. Care has been taken to avoid providing any information that may be used to identify any of these events by name.

3.2 UGT DATA COMPILATION AND EVALUATION.

Available free-field acceleration records from 28 free-field measurement locations in the four events listed above were reviewed. Only those with peak accelerations of about 250 g or less were selected for further evaluation. This "cutoff" was selected, even though accelerations of this level are far greater than accelerations of interest to the earthquake engineering community, in order to assure that no useful UGT records were inadvertently eliminated from consideration. Accelerometer records made at 21 locations at or near the surface of the mesas during these events were also reviewed. For most measurement locations, records from three components (radial, transverse, and vertical) were available.

All of the selected records were evaluated for internal consistency and believability. All but four of the records were provided to us in digital form suitable for use in computing response spectra. Four records from Event 5 were "hand digitized."

3.3 EVALUATION OF EARTHQUAKE SPECTRA.

We reviewed and evaluated the spectra from all of the acceleration time histories that are available from California Strong Motion Instrumentation Program for the Landers (28 June 1992) and Northridge (17 January 1994) earthquakes. The data were processed and spectra were developed by others under the auspices of the California Department of Conservation, Division of Mines and Geology.

Numbers of spectra evaluated in various measurement categories were as follows:

Landers	- 52 ground motion channels
	- 28 channels in buildings
	- 70 channels on bridges
Northridge	- 231 ground motion channels
	- 133 channels in buildings
	- 4 channels on a bridge
	- 3 channels on a dam abutment

Spectra were evaluated for consistency with other earthquake spectra and for peak spectral velocity. Spectral velocities from the ground motion records and the measurements made on bridges were generally much lower than those from measurements made in the upper stories of buildings. No attempt was made to correlate spectral peaks with range from the epicenter. The shapes of the earthquake response spectra were generally very similar, regardless of peak values and measurement location.

Peak spectral velocities from ground motion records were generally much lower than those from the available UGT records as discussed subsequently in Section 3.5. Therefore, we developed predicted spectra for earthquakes of larger magnitude and at shorter ranges as discussed in the next subsection.

3.4 PREDICTIONS OF EARTHQUAKE RESPONSE SPECTRA.

Response spectra predictions were made using a prediction method developed by Boore, Joyner, and Fumal of the U. S. Geological Survey (Boore, 1993 and Boore, 1994). Equations are available for

> ... predicting the larger horizontal and the random horizontal component of peak acceleration and of 2-, 5-, 10-, and 20-percent-damped pseudo-velocity [spectral velocity as defined in Section 2.1] response spectra for 46 periods ranging from 0.1 to 2.0 sec. The equations were obtained by fitting functional form to empirical data using a two-stage regression method. 271 two-component recordings from 20 earthquakes were used to develop the equations for peak acceleration, and 112 two-component recordings from 14 earthquakes were used for the response spectral equations.

The user of the prediction equations must select a value for each of the following three variables:

- Earthquake magnitude (less than or equal to M7.7)
- Average shear wave propagation velocity in the upper 30 meters of soil at the site of interest
- Distance* (range) from the earthquake fault to the site of interest

Predictions were developed for several combinations of the above variables in an attempt to obtain peak spectral velocities comparable to those from the available UGT records. Some representative examples of spectral predictions are shown in Figures 3-1 and 3-2 for magnitude 6.7 and 7.7 earthquakes, respectively. In these and subsequent tripartite plots, the spectral quantities are as defined in Section 2.1. The vertical axis represents spectral velocity. Spectral accelerations and spectral displacements are shown by the diagonal axes; spectral acceleration (in g's) increases from lower right to upper left, and spectral displacement (in inches) increases from lower left to upper right.

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* Defined in (Boore, 1993) as "the closest horizontal distance from the station to the point on the earth's surface that lies directly above the rupture"

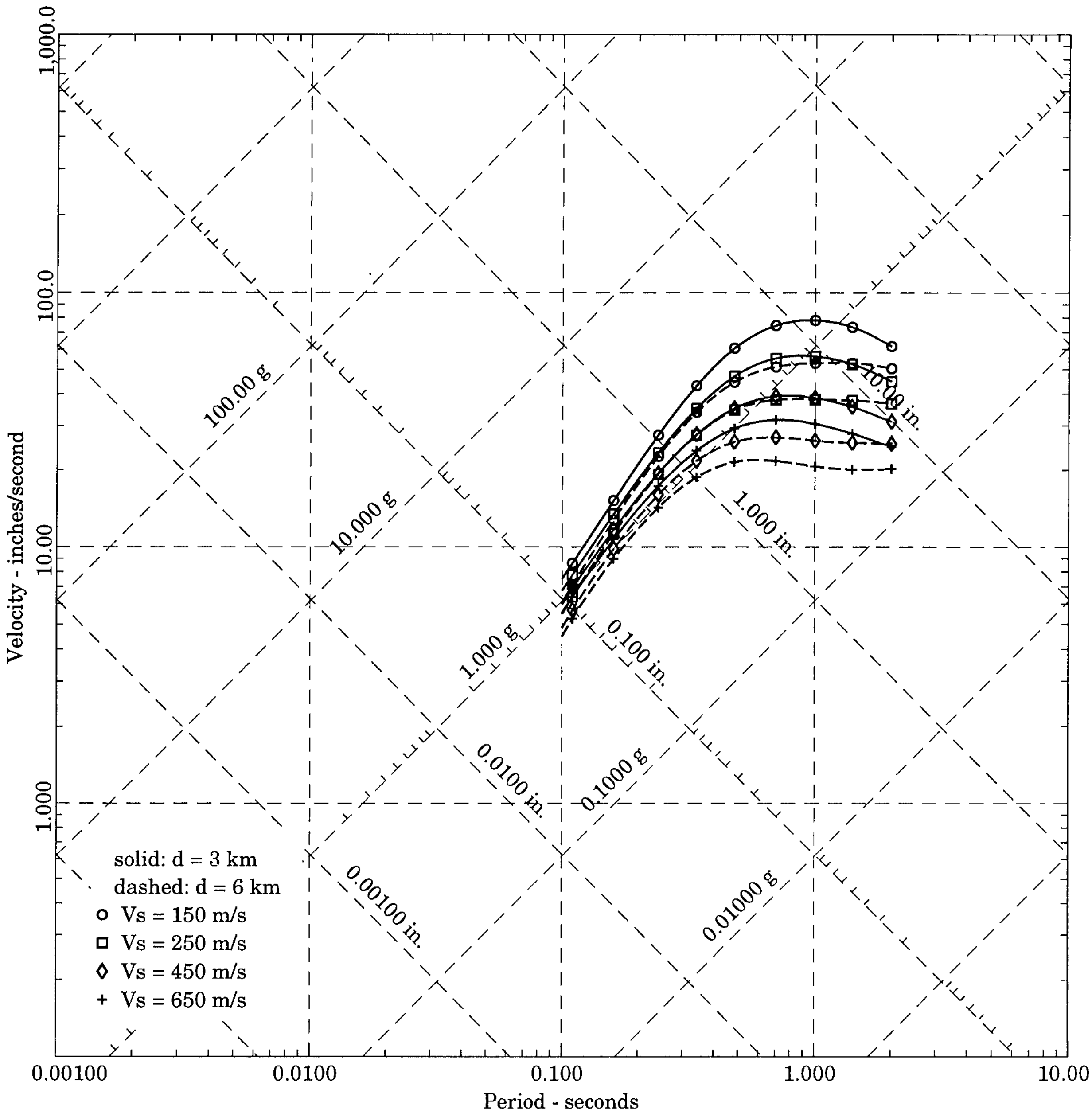


Figure 3-1. Predicted response spectra for M6.7 earthquakes.

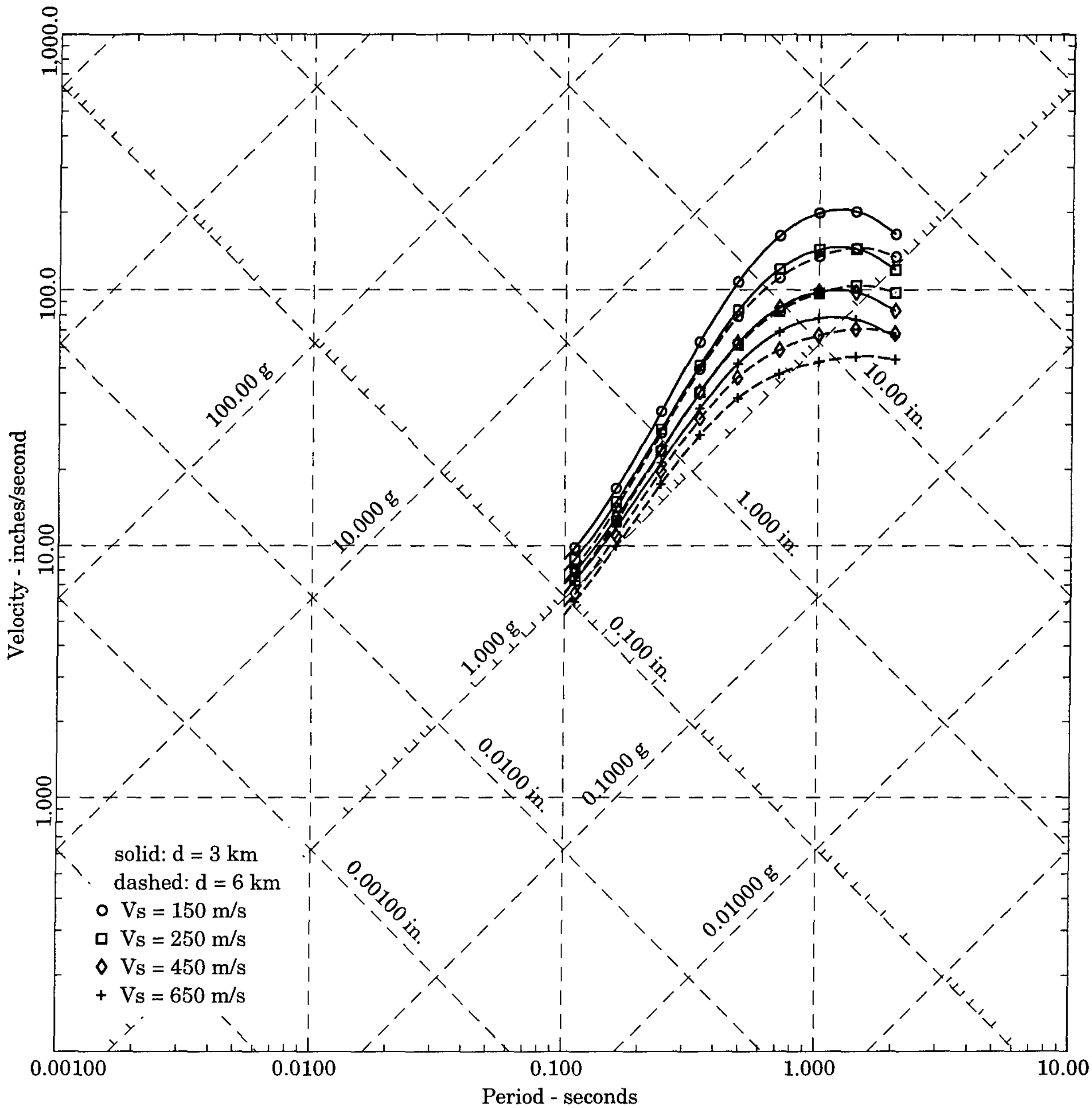


Figure 3-2. Predicted response spectra for M7.7 earthquakes.

In both Figures 3-1 and 3-2, the solid curves are for a range from the fault of 3 kilometers, and the dashed curves are for a range of 6 kilometers. As indicated by the legends on the figures, selected shear wave propagation velocities range from 150 meters per second to 650 meters per second. Note that the lower the shear wave propagation velocity, the higher the spectral response.

The shapes of the response spectra are very similar, and in all cases, peak spectral velocity occurs at a period of approximately one second. For the M7.7 earthquake (Figure 3-2), three of the peak spectral velocities fall between 100 and 200 inches per second. It is possible to predict larger spectral velocities, but only by selecting very small ranges and very low (probably unreasonably low) values of the shear wave propagation velocity.

3.5 EVALUATION OF UGT RESPONSE SPECTRA.

Response spectra were developed for all of the UGT acceleration time histories that were described in Section 3.2. Integration and plotting limits used for these spectra are:

- Largest period for which a spectrum is computed was taken (arbitrarily) as five times the record length
- Smallest period for which a spectrum is computed was taken as ten times the largest digitization interval
- Integration time step was selected to be one-fiftieth of the smallest period for which a spectrum is computed

A study by Nigam and Jennings (Nigam, 1969) indicated that selection of an integration time step as large as one-twentieth of the period will provide spectra that are accurate to within about one percent. Therefore, our time step selection is conservative.

As a first step, all spectra computed from radial free-field UGT acceleration time histories measured at tunnel bed level (as opposed to measurements at or near the surface of the mesa) were reviewed and evaluated. Fourteen spectra were identified

with peak spectral velocities of about 200 inches per second or less, making them comparable to the predicted earthquake spectra shown in Figures 3-1 and 3-2. These are:

- Event 5 - three records from three different ranges
- Event 6 - one record
- Event 25 - ten records from nine different ranges

Some of these spectra were selected for comparison with earthquake spectra as described in the next subsection.

3.6 COMPARISON OF UGT WITH EARTHQUAKE SPECTRA.

Ten of the UGT spectra referred to at the end of the preceding subsection are plotted as follows:

- Event 5 - Figures 3-3 through 3-5
- Event 6 - Figure 3-6
- Event 25 - Figures 3-7 through 3-12

Seven of the Event 25 measurements were made at 25 meter intervals from 200 to 350 meters range. Spectra from three of these (measurements made at ranges of 200, 275, and 350 meters) are shown in Figures 3-10 through 3-12, respectively.

In each figure, at least one predicted earthquake spectrum and at least one spectrum from an actual record from the Northridge earthquake are plotted in addition to the UGT spectrum. Each figure caption identifies the UGT record (event number and record designation) associated with the spectrum plotted in that figure.

The first entry in the legend for each figure also identifies the UGT record. The predicted ground motion spectra identifiers begin with "B/J"; they also indicate the values of the three variables used in the prediction equations. For example, in Figure 3-3, the identifier "B/J M:6.7, Vs:150, d:0.5" indicates a prediction using the Boore, Joyner, and Fumal method for (1) magnitude 6.7 earthquake, (2) shear wave propagation velocity of 150 meters per second, and (3) range from the earthquake fault of 0.5 kilometers.

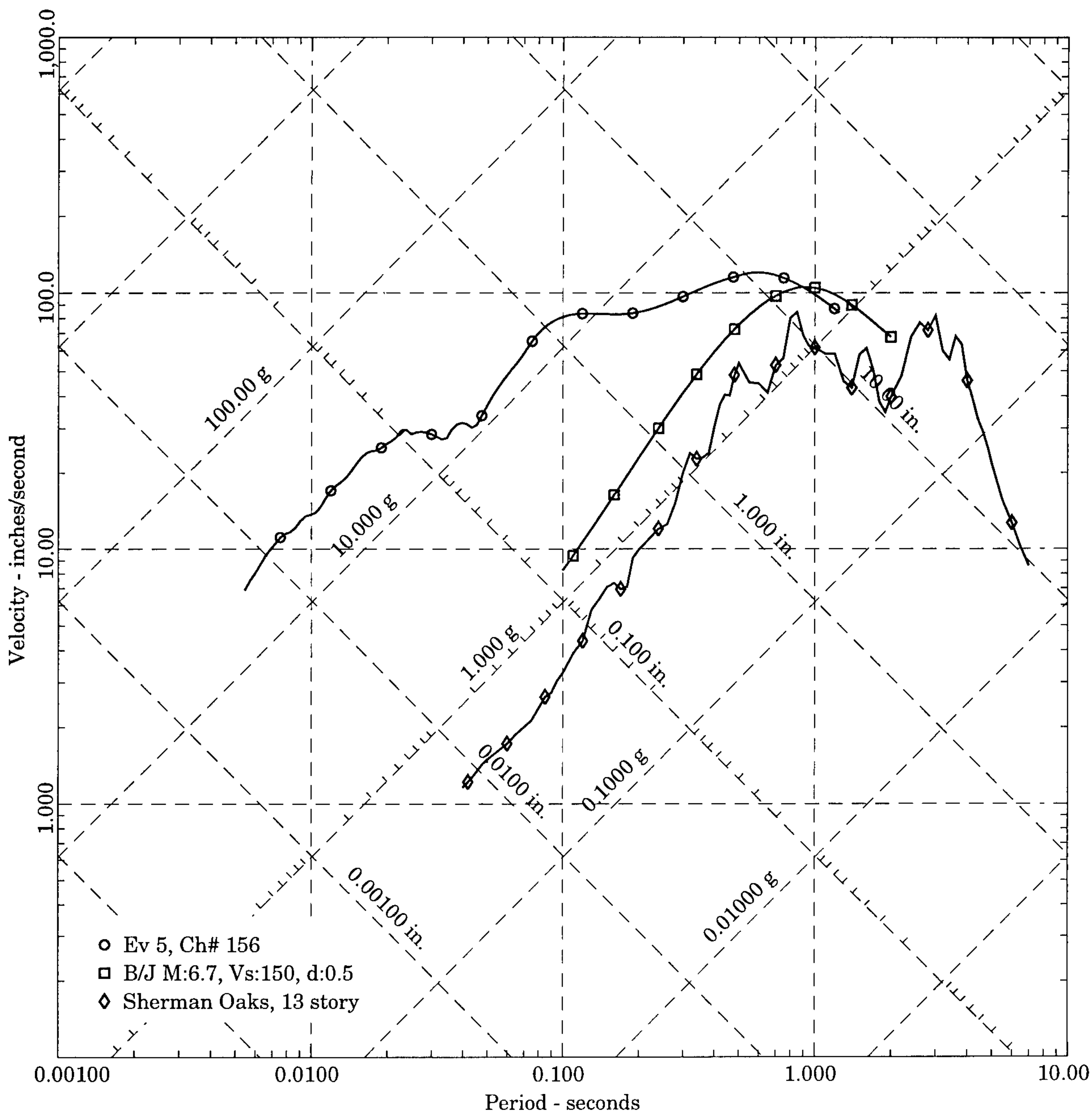


Figure 3-3. Event 5, Channel #156 spectrum compared with earthquake spectra.

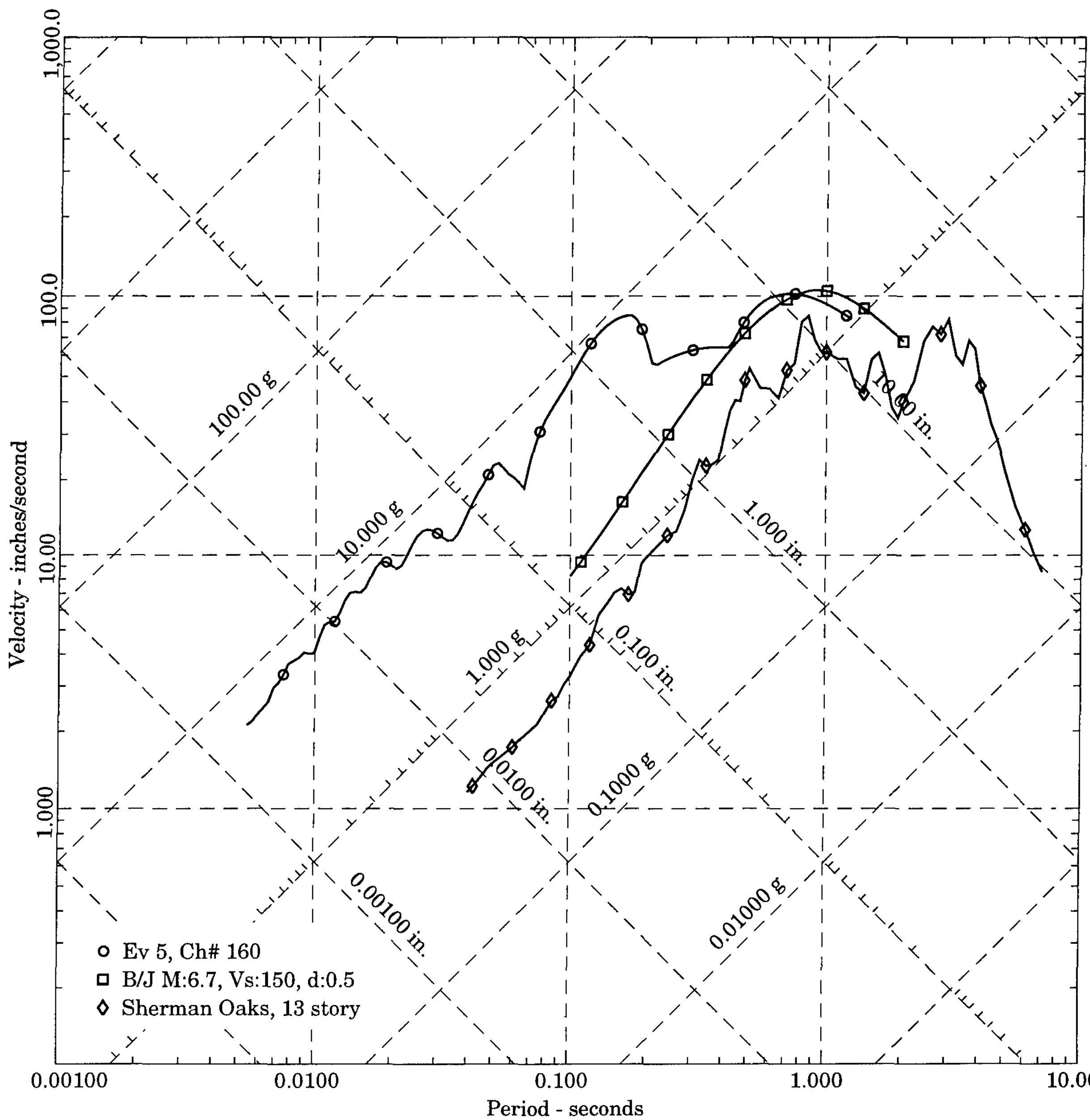


Figure 3-4. Event 5, Channel #160 spectrum compared with earthquake spectra.

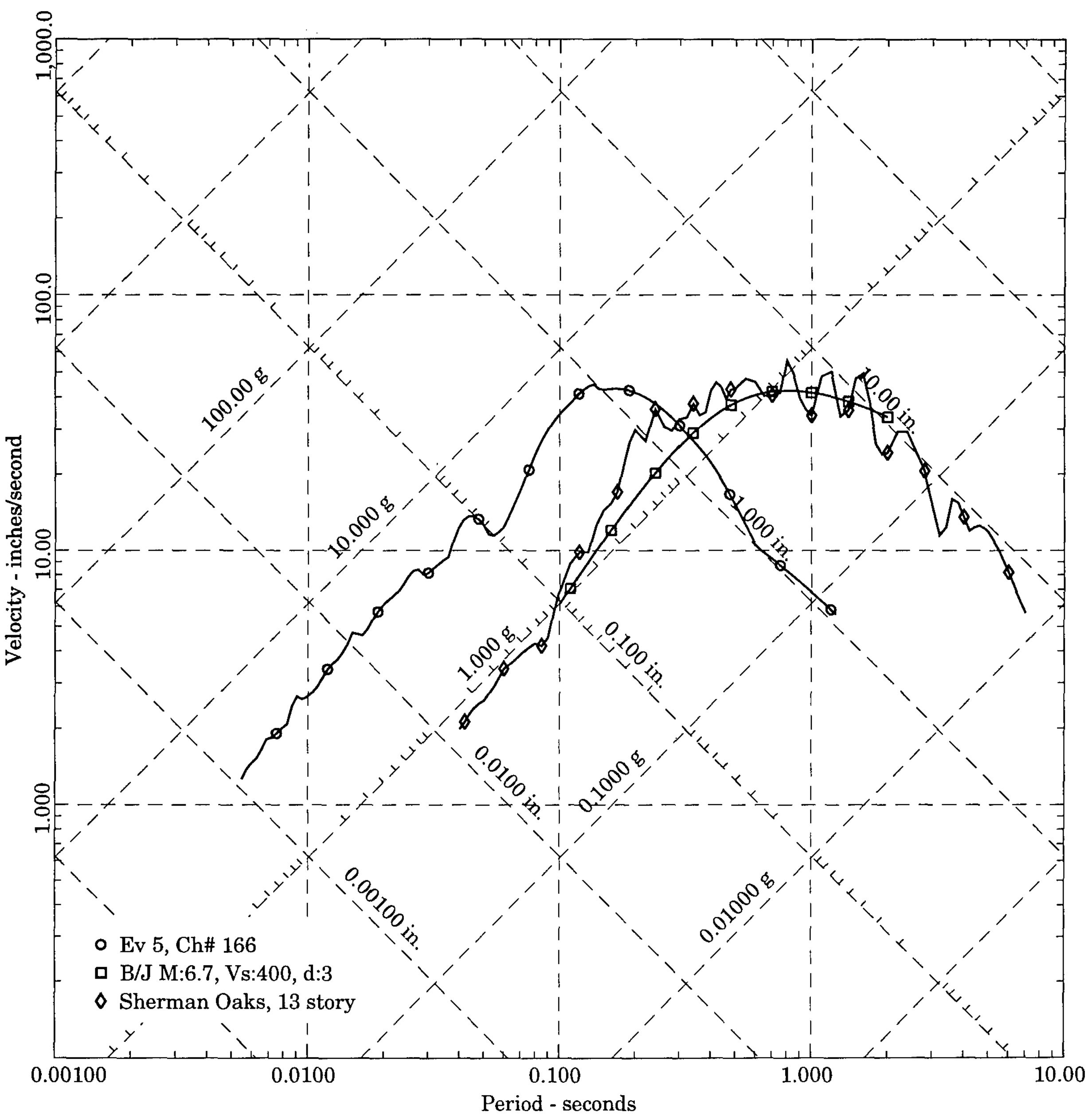


Figure 3-5. Event 5, Channel #166 spectrum compared with earthquake spectra.

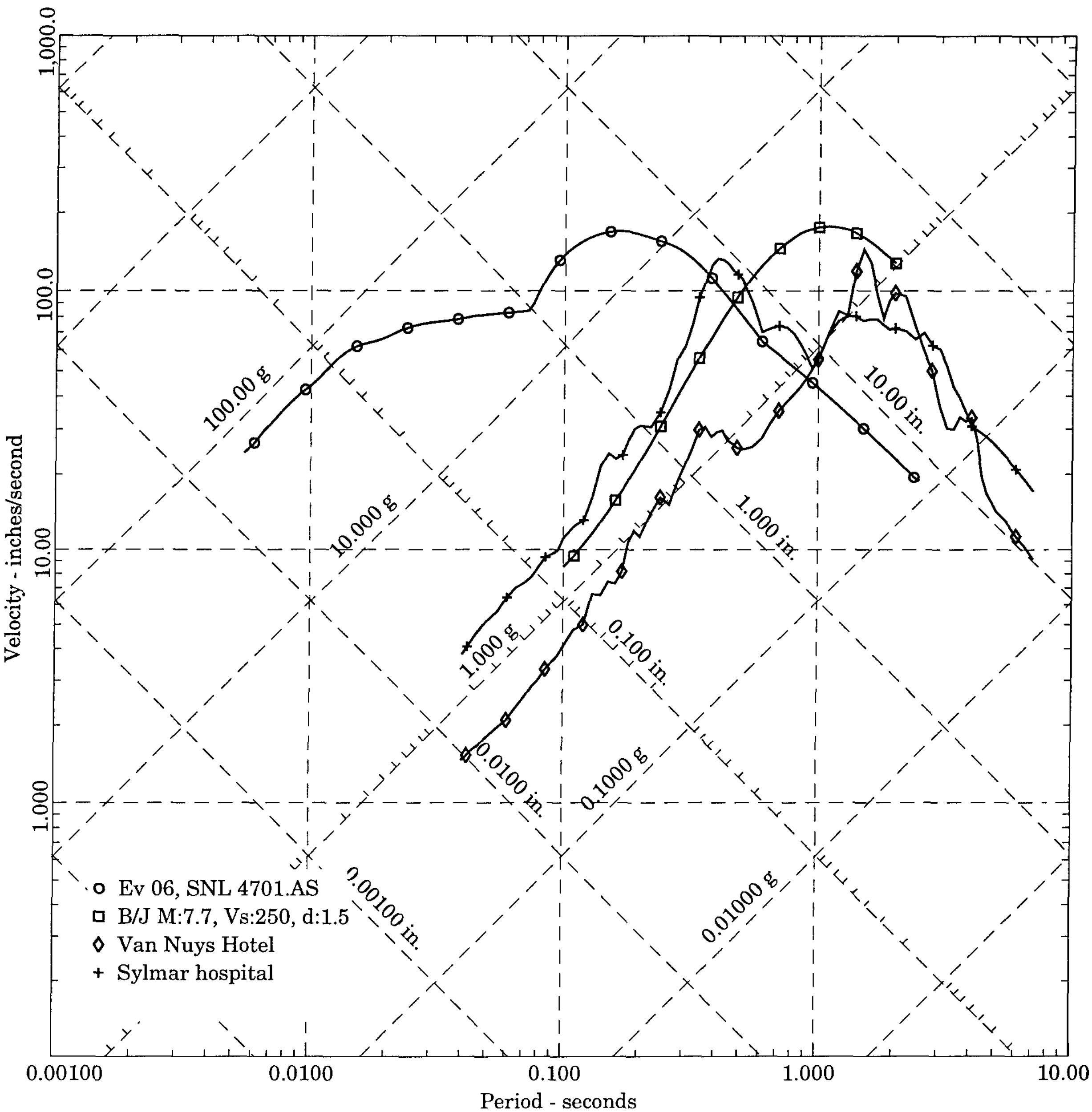


Figure 3-6. Event 6, SNL 4701.AS spectrum compared with earthquake spectra.

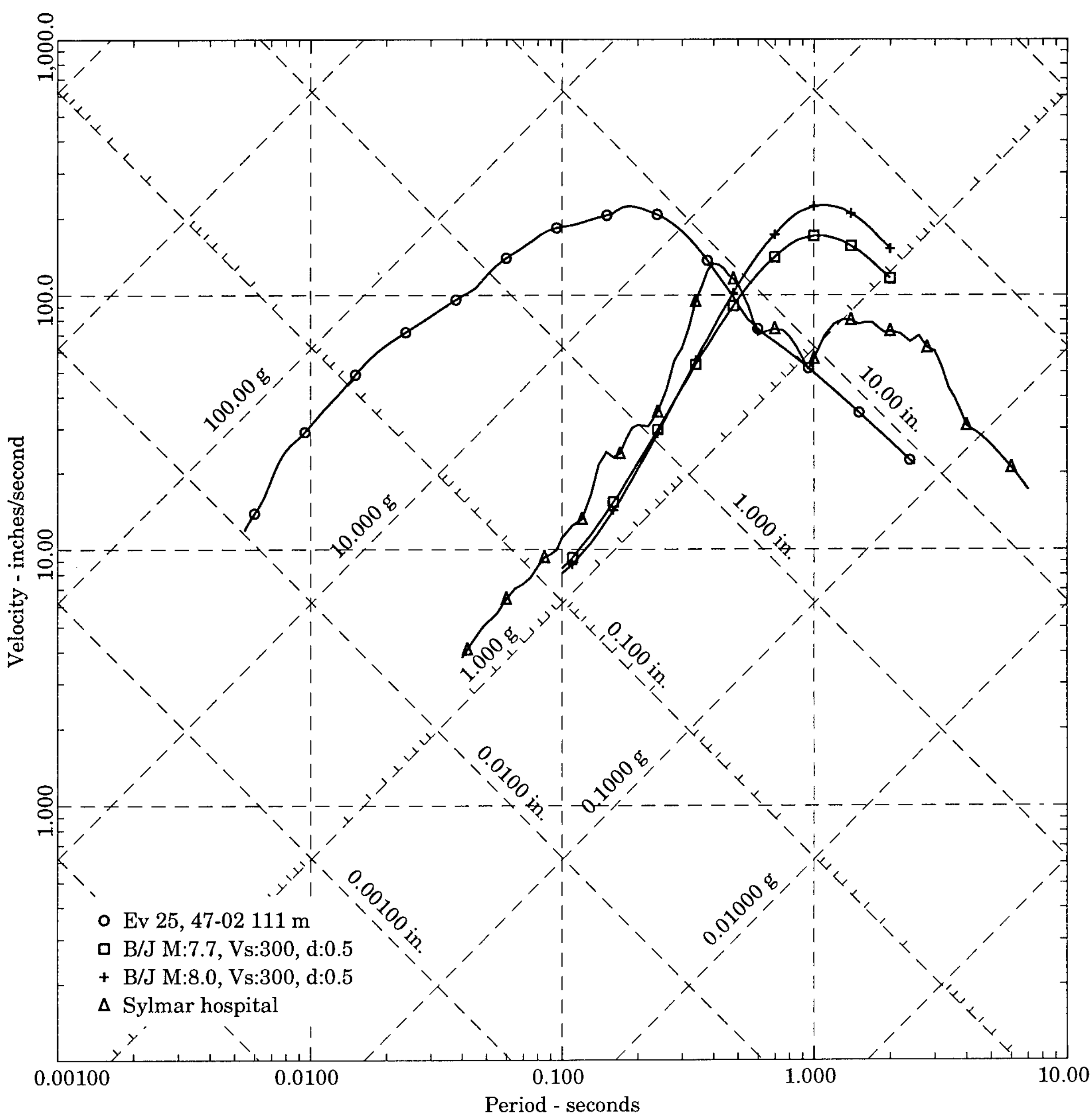


Figure 3-7. Event 25, 47-02 111m spectrum compared with earthquake spectra.

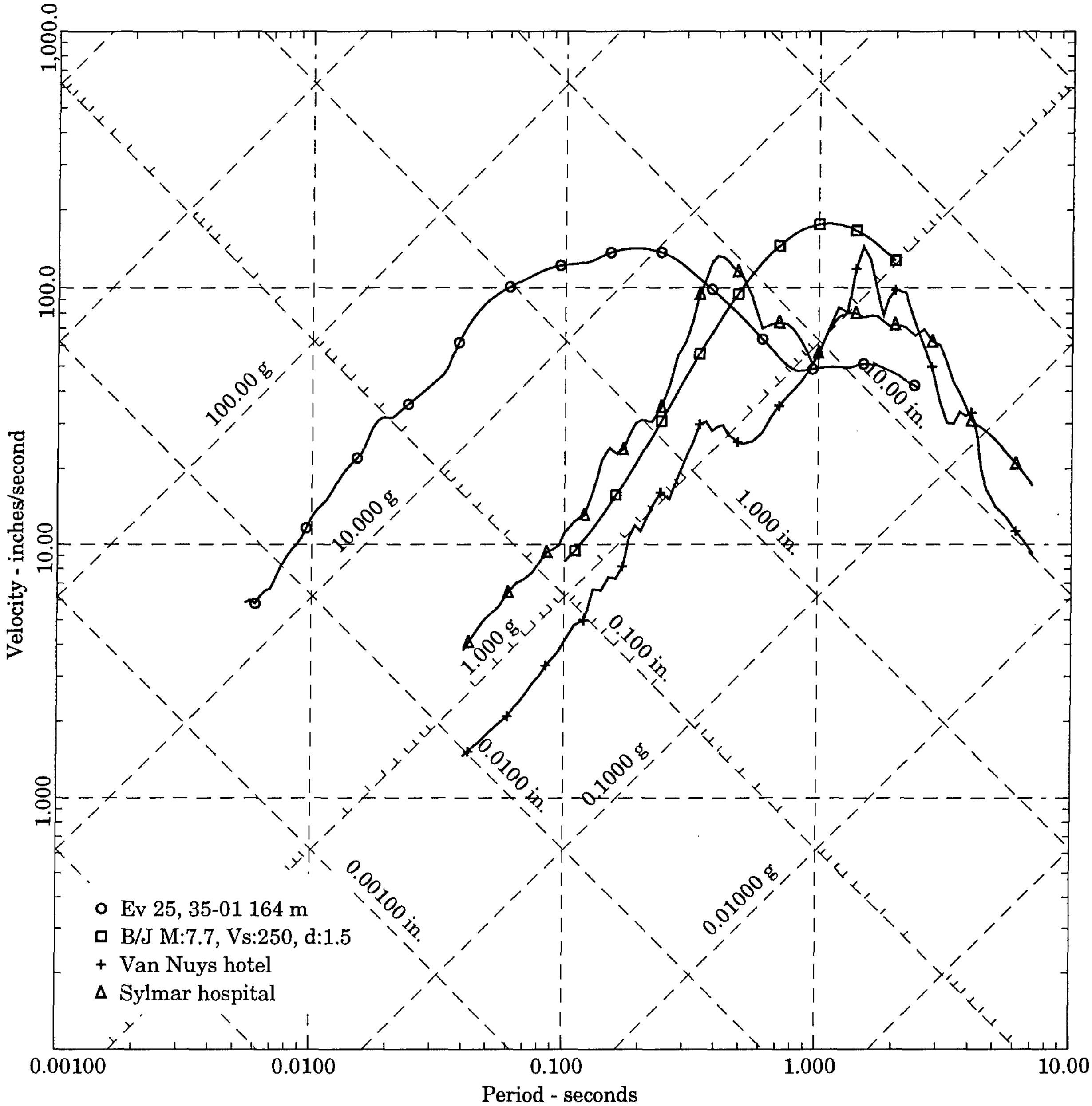


Figure 3-8. Event 25, 35-01 164m spectrum compared with earthquake spectra.

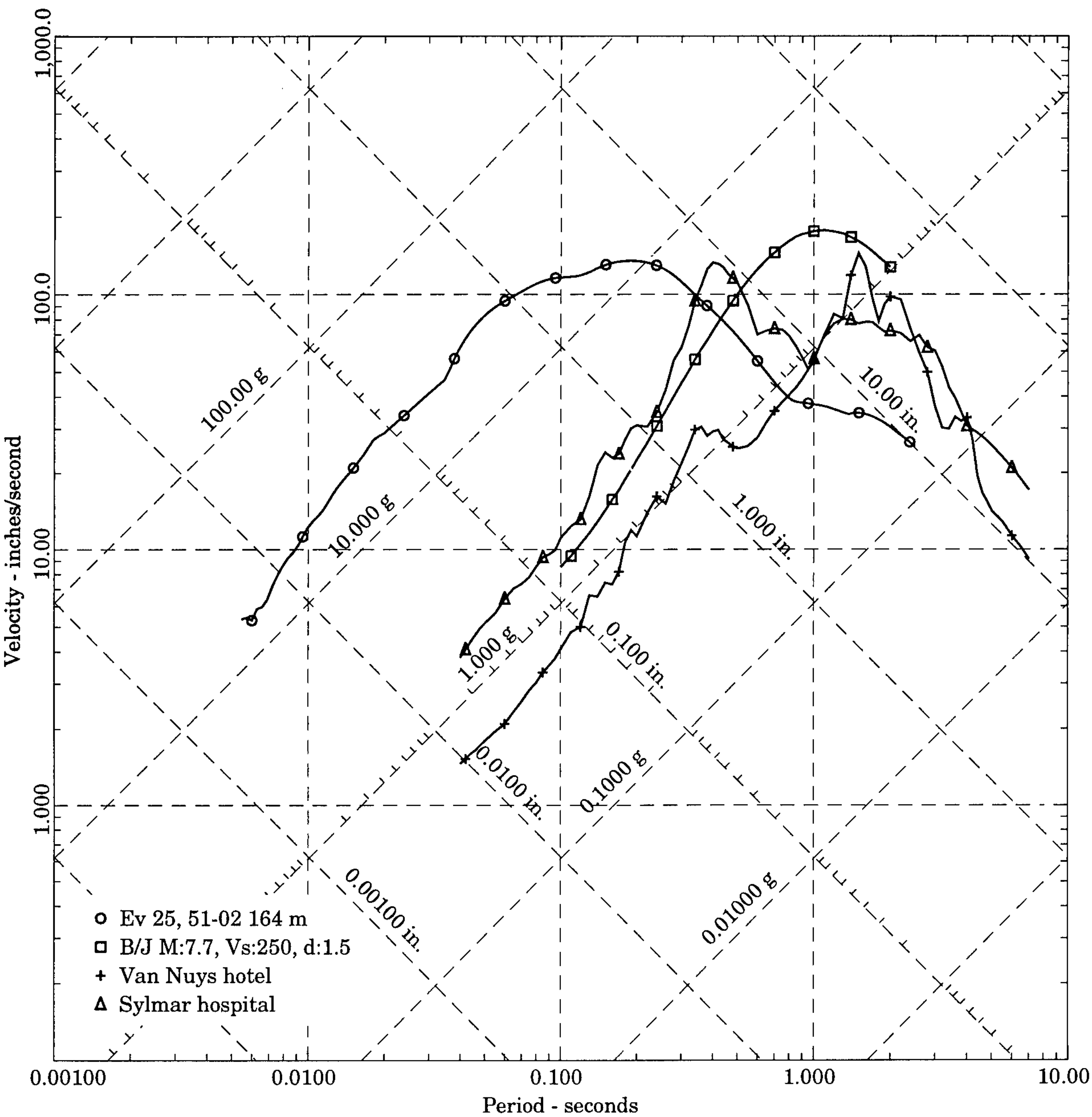


Figure 3-9. Event 25, 51-02 164m spectrum compared with earthquake spectra.

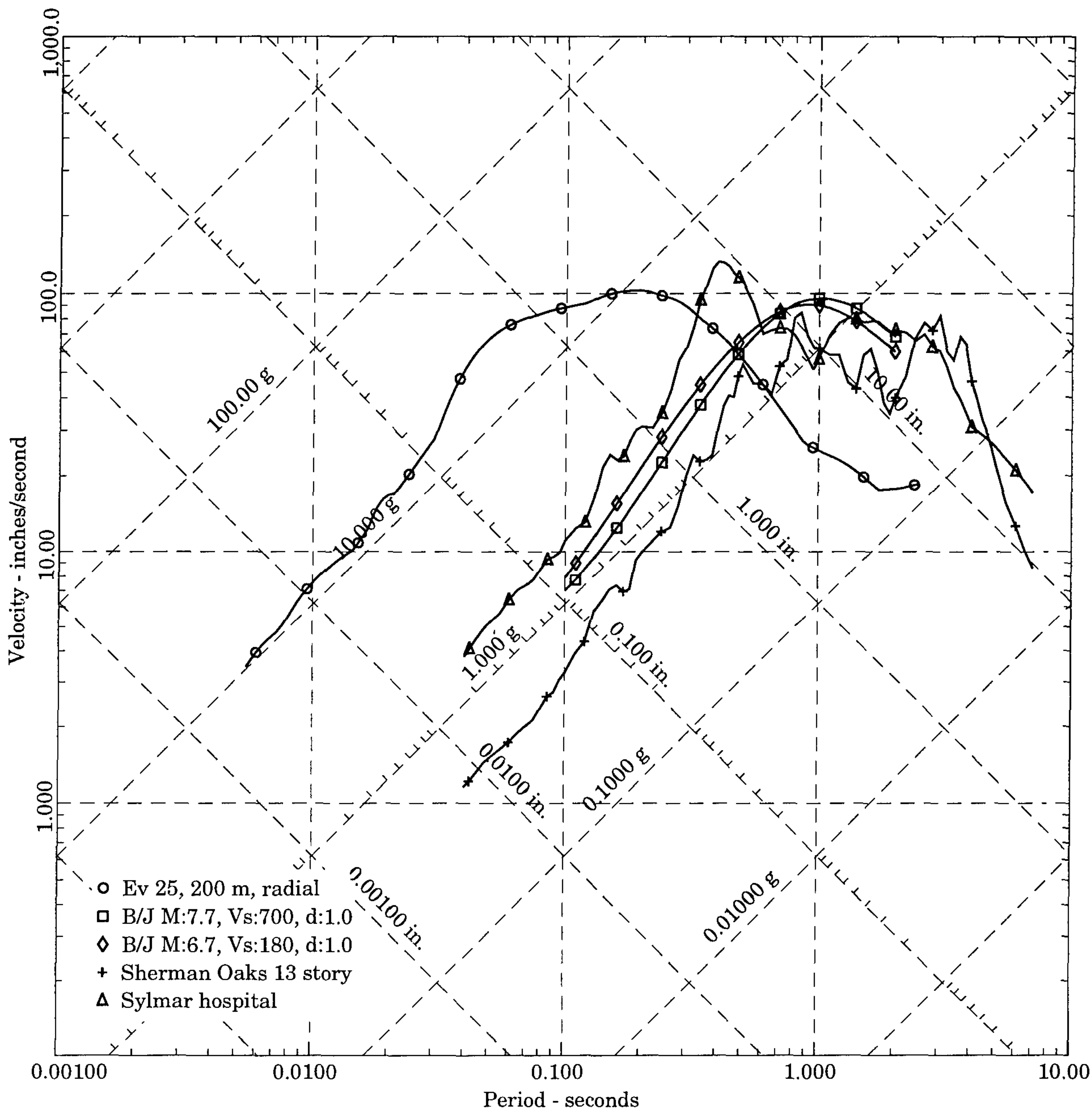


Figure 3-10. Event 25, 200 meter spectrum compared with earthquake spectra.

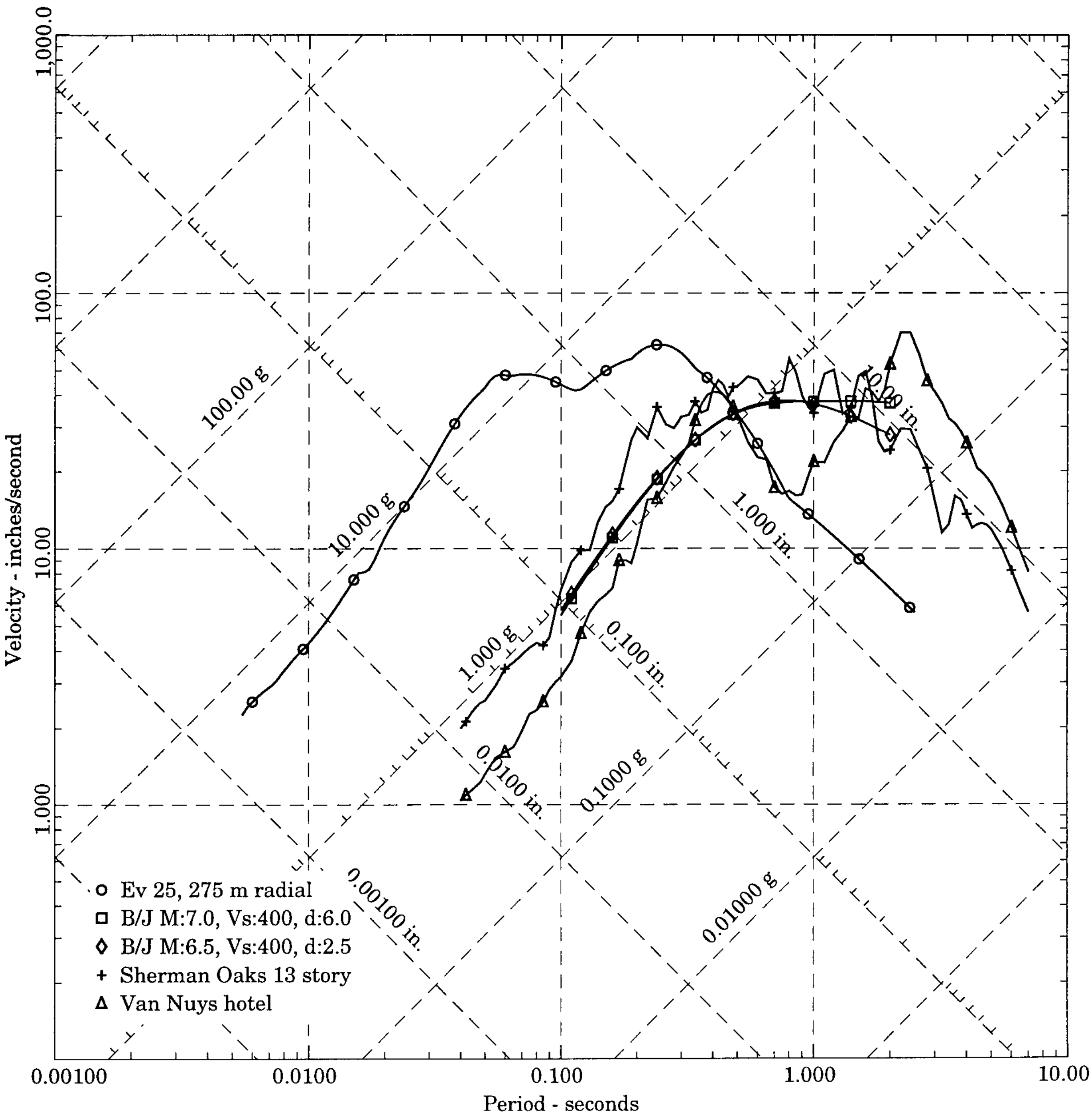


Figure 3-11. Event 25, 275 meter spectrum compared with earthquake spectra.

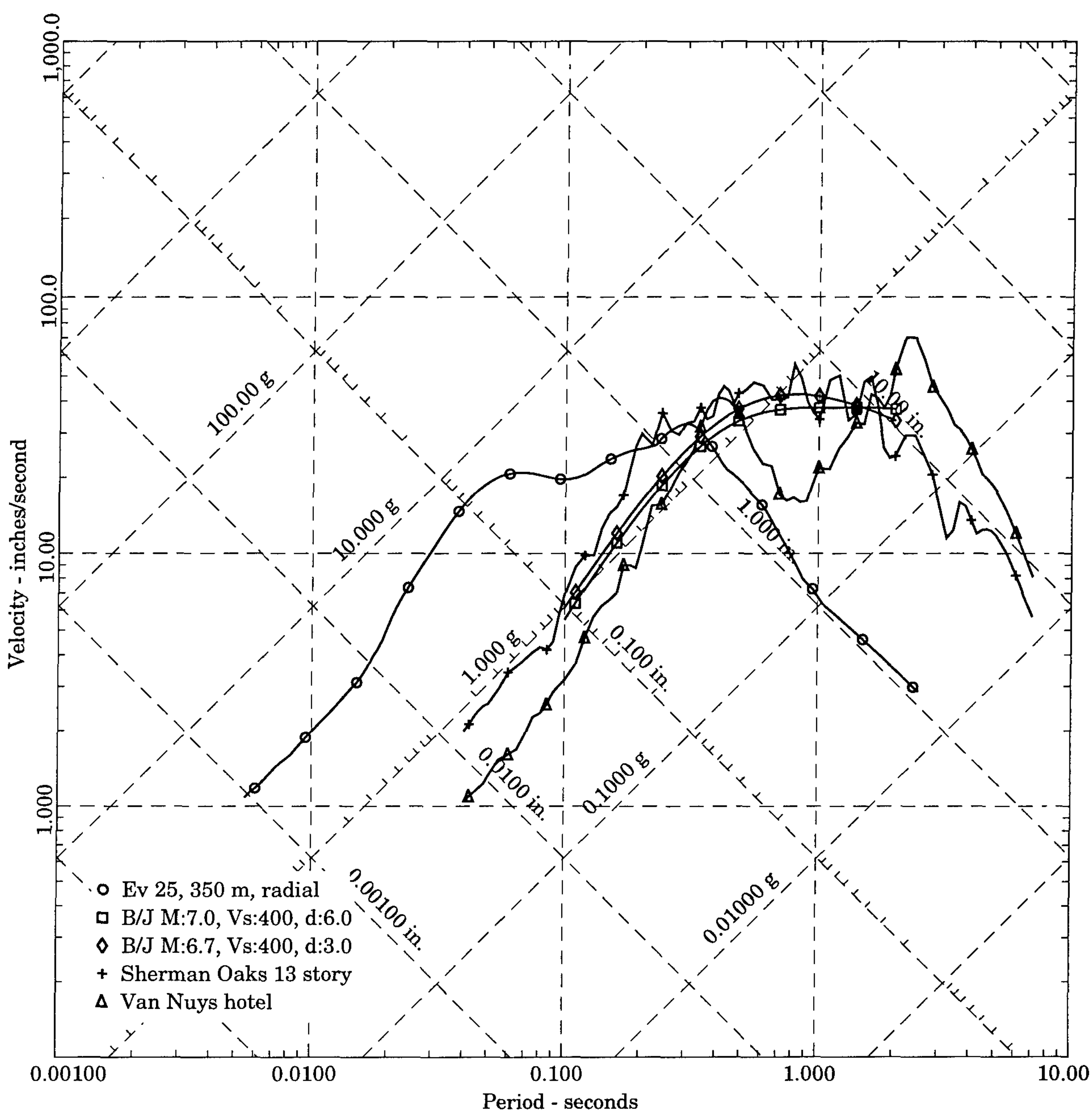


Figure 3-12. Event 25, 350 meter spectrum compared with earthquake spectra.

Spectra from actual earthquake records are identified by building designations, e.g., "Sherman Oaks, 13 story" in Figure 3-3 indicates the spectrum from a measurement made in a 13-story building located in Sherman Oaks, California. Most of the actual earthquake spectra are from measurements made in upper stories or on the roofs of multistory buildings. These spectra and the predicted ground motion spectra were selected so that their peak spectral velocities would be approximately equal to the peak spectral velocity in the UGT spectrum plotted in the same figure.

3.7 NON-RADIAL AND SURFACE RECORDS.

All of the comparisons of UGT spectra with earthquake spectra discussed above used UGT spectra from radial measurements. Radial ground motions are believed to be almost entirely dilatational in nature. Therefore it appeared reasonable to expect that spectral velocities from non-radial and surface measurements made during UGTs might peak at longer periods and thus compare more favorably with those observed in earthquake spectra. Consequently, this question was addressed as described below.

As a first step, spectra from the radial, transverse, and vertical components at several underground measurement locations were compared with each other. Peak spectral velocities from the transverse and vertical components are significantly lower than those from the radial components. Figures 3-13, 3-14, and 3-15 show spectra from radial, transverse, and vertical measurement components, respectively, from seven underground measurement locations in Event 25. Measurement ranges are identified in the legend at the upper right in each of these and the three subsequent figures. Spectral velocities from all three measurement components peak at periods between about 0.08 and 0.25 second (well below the one second or greater periods at which typical earthquake spectra peak). Also, the shapes of all of the spectra for all three measurement orientations are qualitatively similar.

Spectra from surface measurements made at four locations in Event 13 were also considered. These spectra from radial, transverse, and vertical measurement components are shown in Figures 3-16, 3-17, and 3-18, respectively. These spectra are from records made by gages that were originally installed for a different event. Hence, the terms radial and transverse do not refer to the Event 13 working point; for this discussion, that does not matter. Peak spectral velocities from the vertical

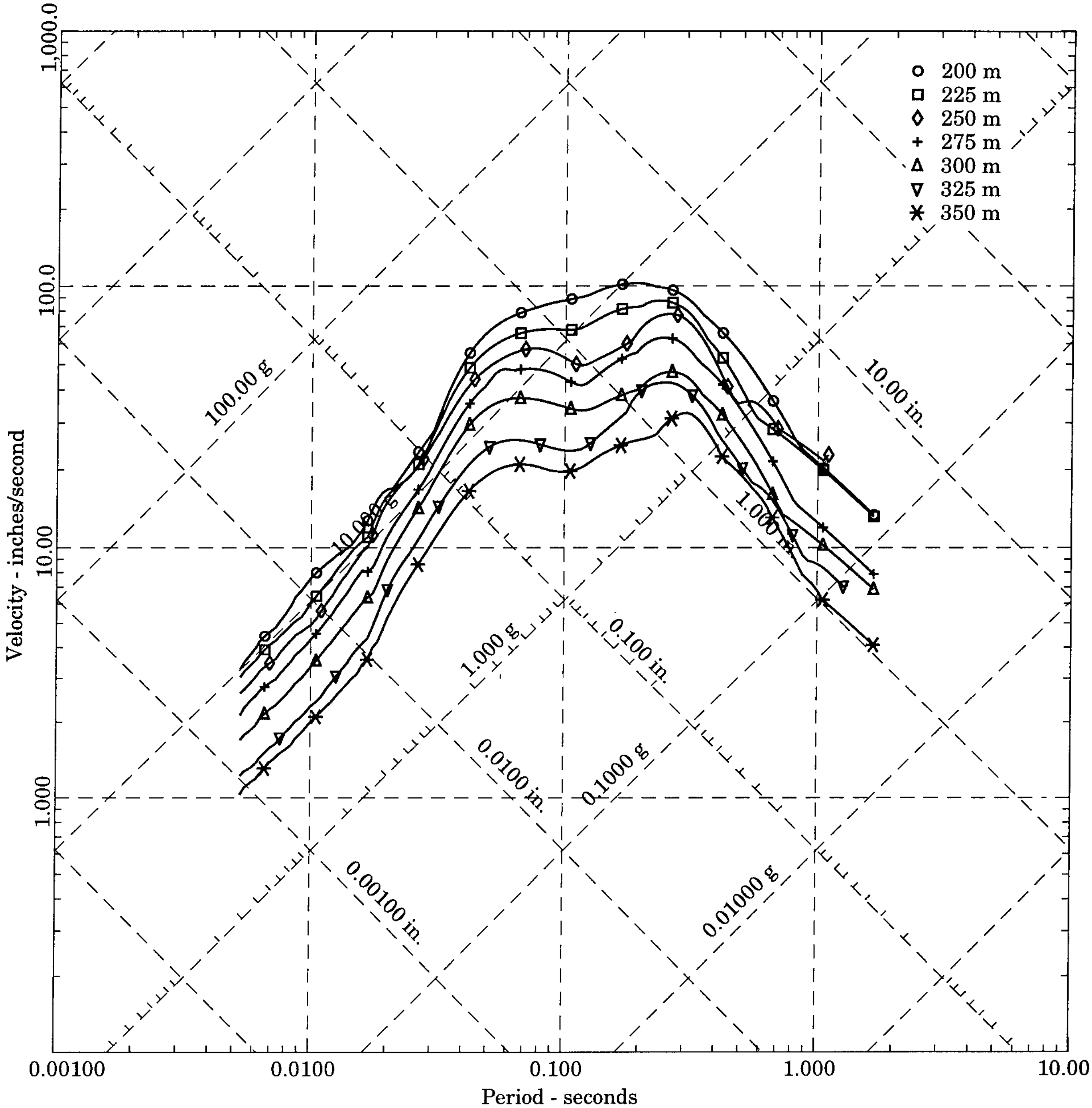


Figure 3-13. Event 25, underground records, radial orientation.

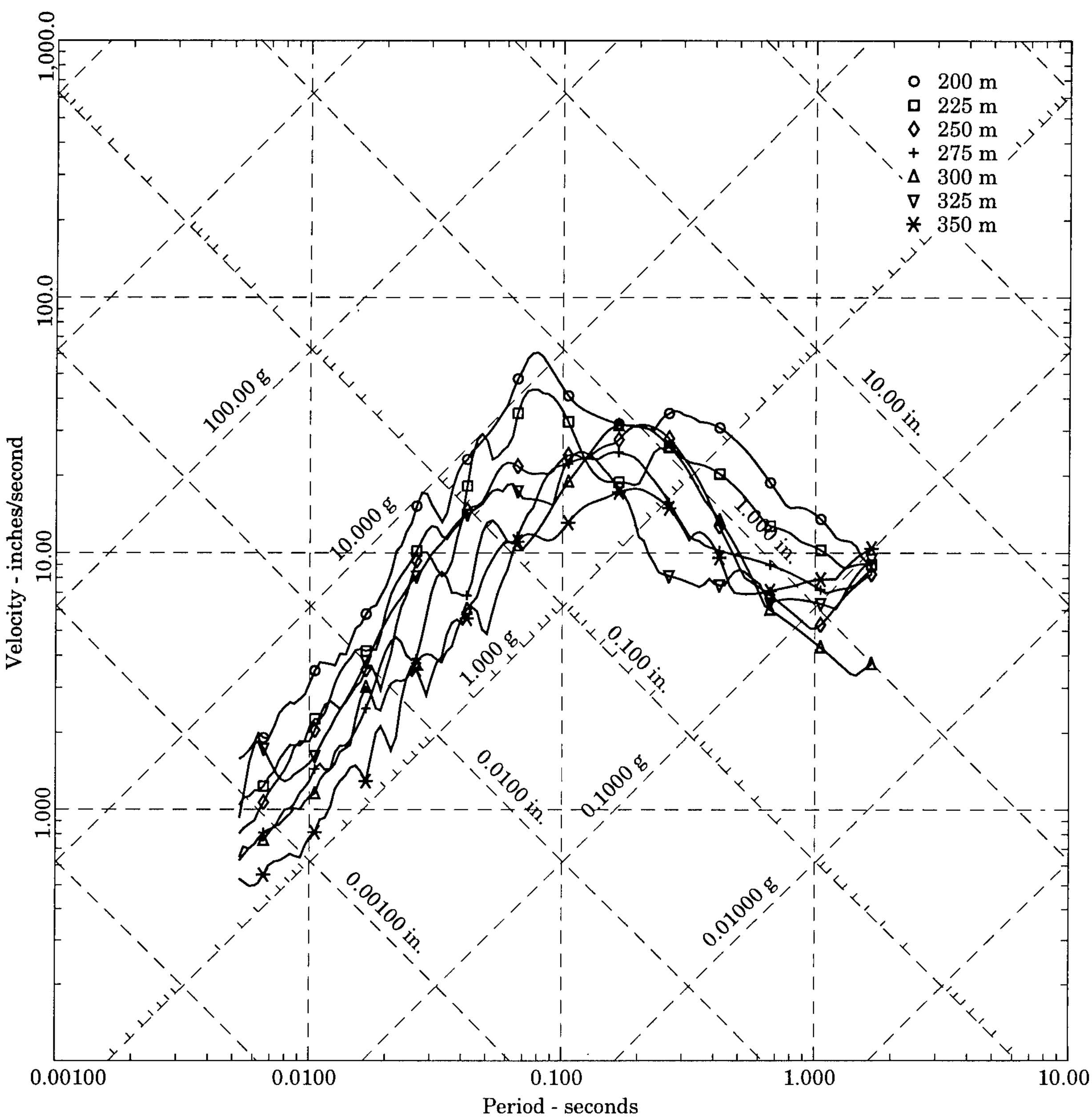


Figure 3-14. Event 25, underground records, transverse orientation.

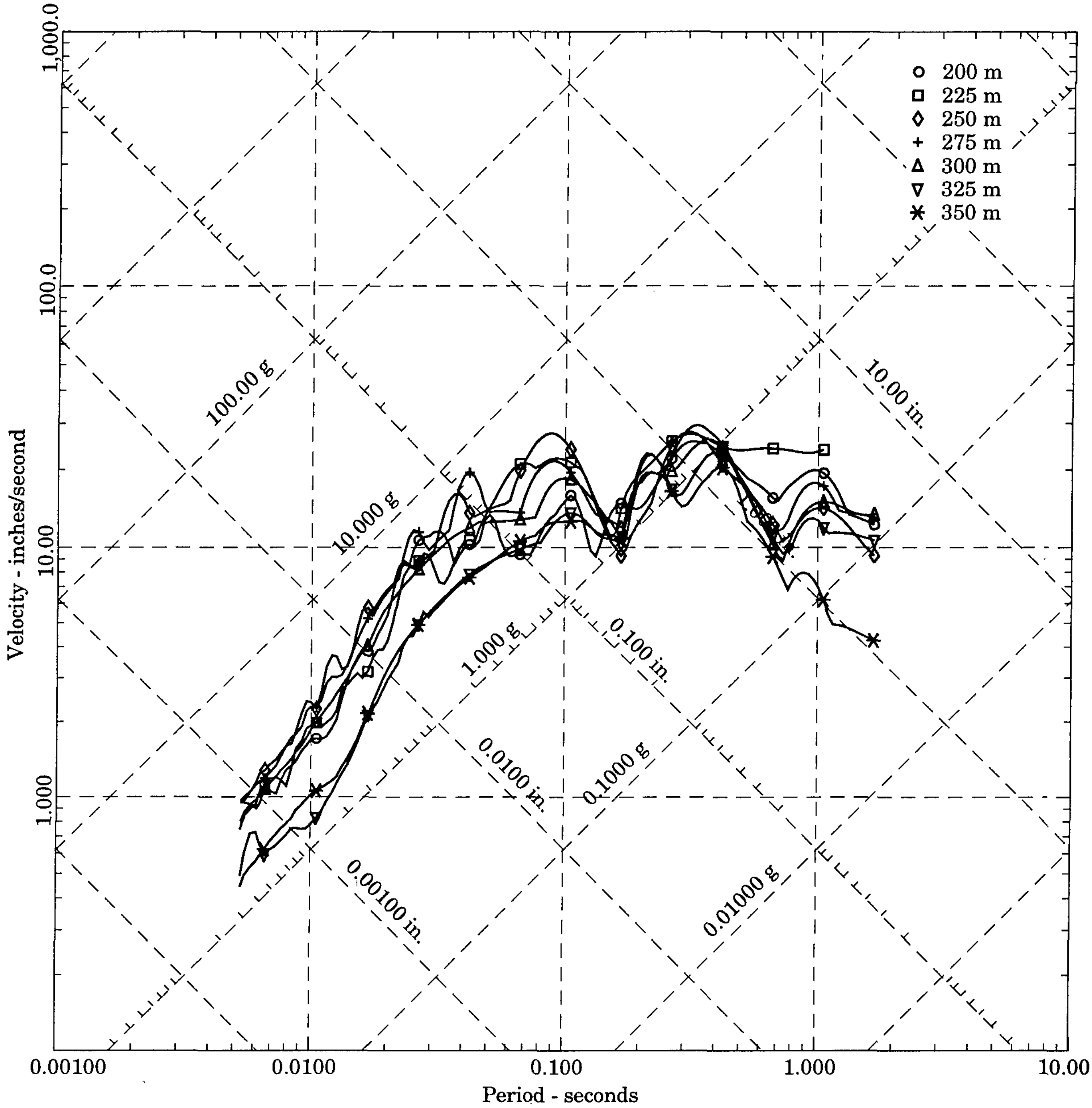


Figure 3-15. Event 25, underground records, vertical orientation.

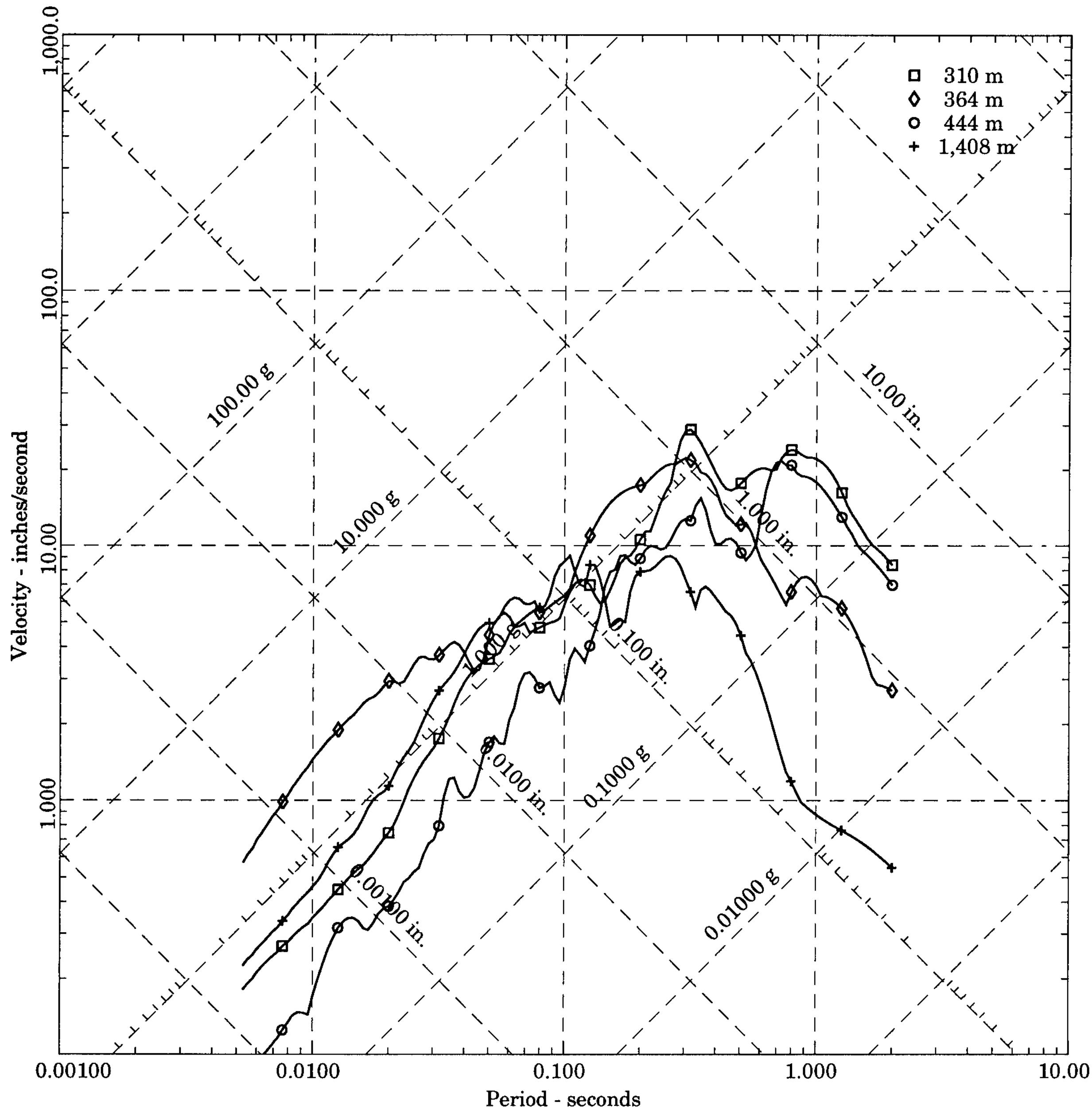


Figure 3-16. Event 13, surface records, radial orientation.

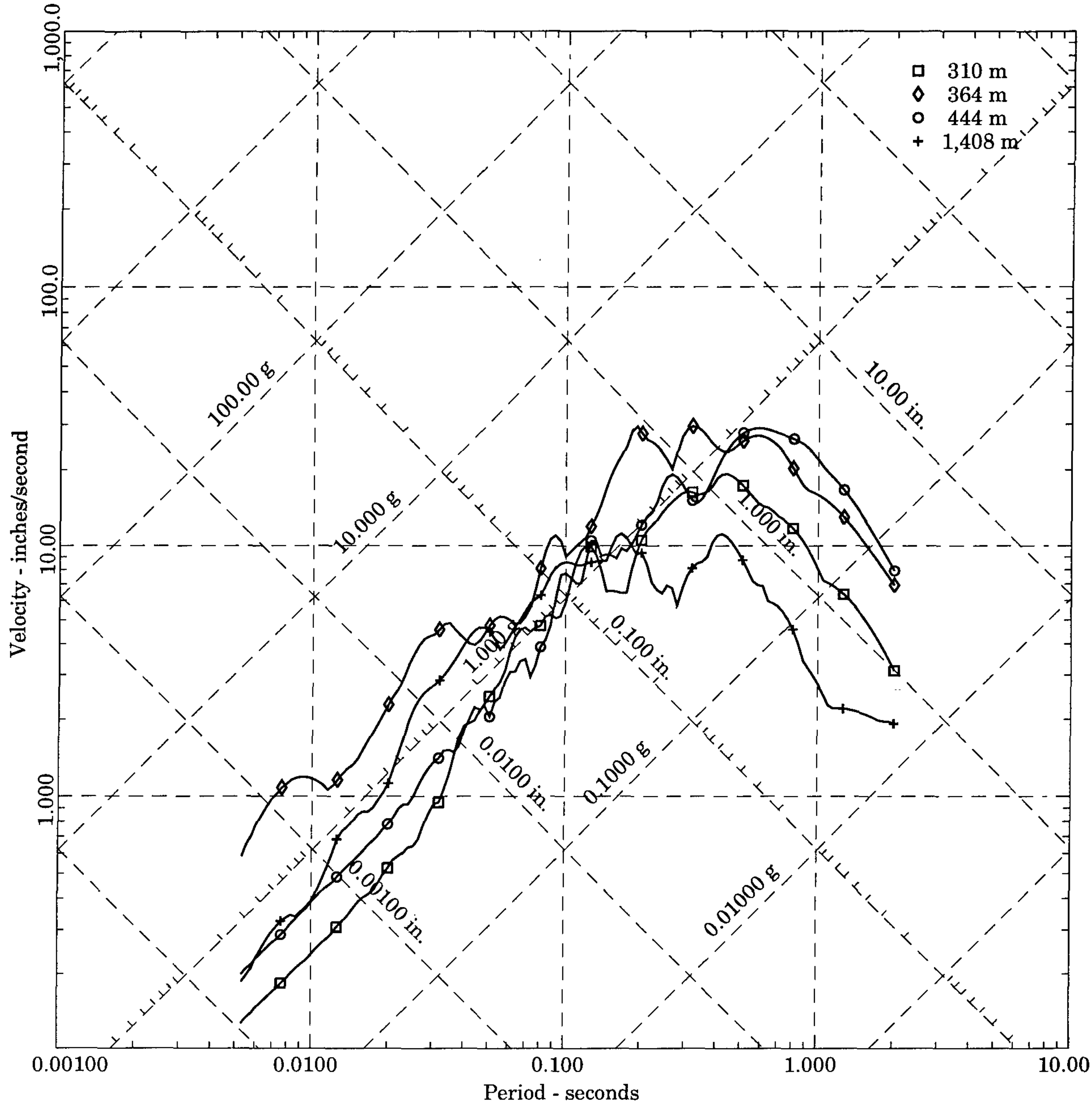


Figure 3-17. Event 13, surface records, transverse orientation.

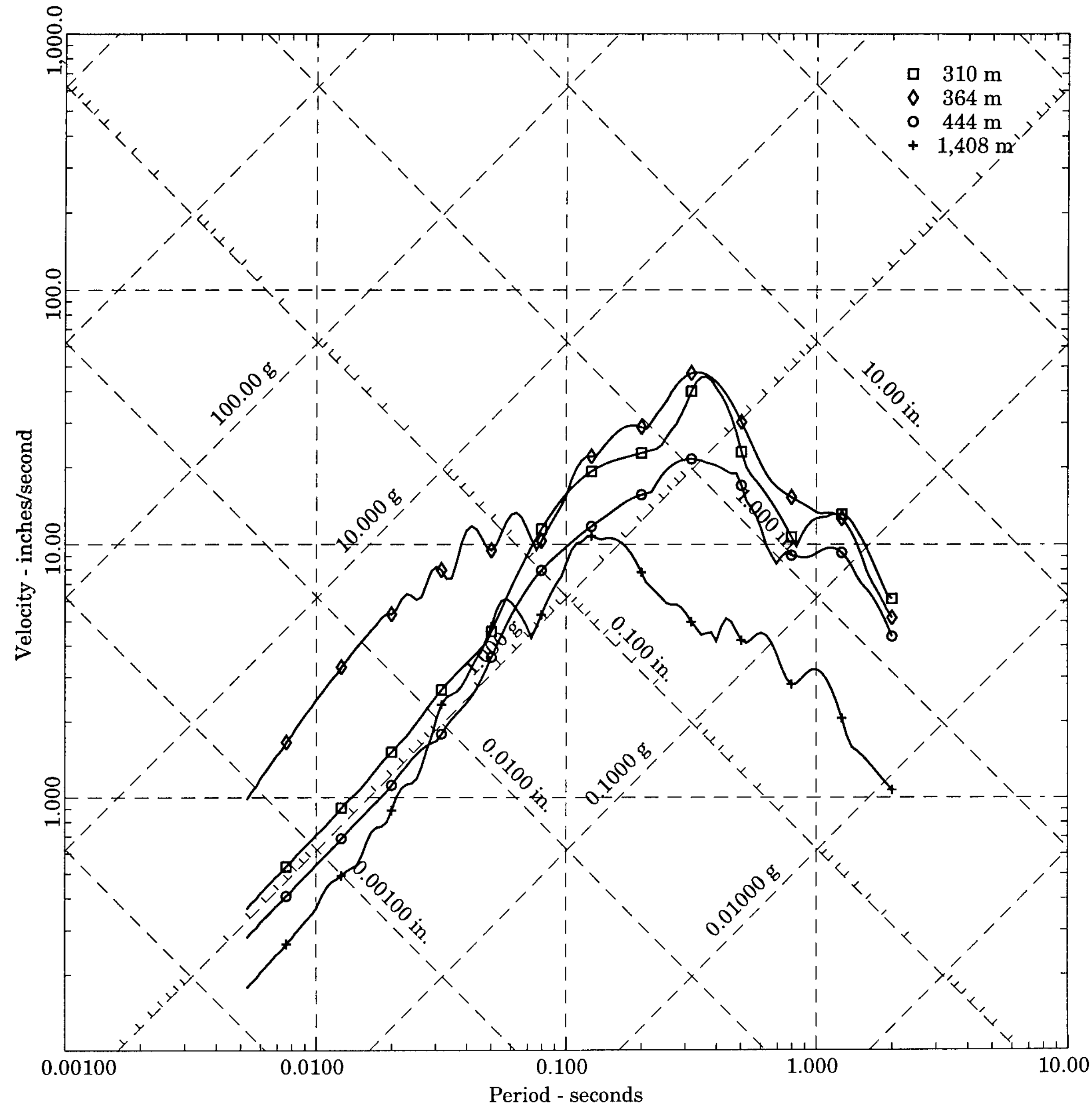


Figure 3-18. Event 13, surface records, vertical orientation.

component are slightly higher than those from the other two components. For all three components, the peak spectral velocities occur at periods of approximately 0.3 second.

This is somewhat higher than the 0.08 to 0.25 second period range discussed above for the underground measurements. However, it is still well below the periods at which typical earthquake spectral velocities peak.

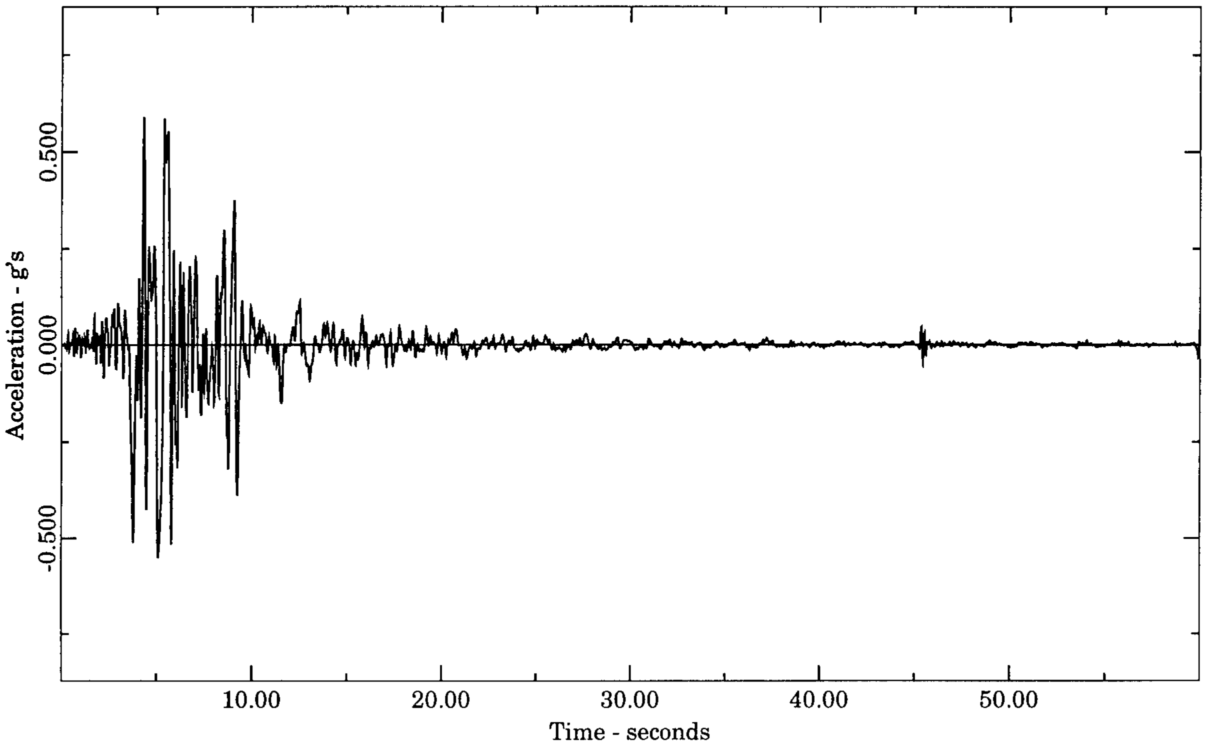
Because of the above observations, we did not plot any earthquake spectra together with either of the two types of UGT spectra discussed above. It does not appear that such plots would be very useful, and this aspect of the project was not pursued further.

3.8 SPECTRA FROM PARTIAL RECORDS.

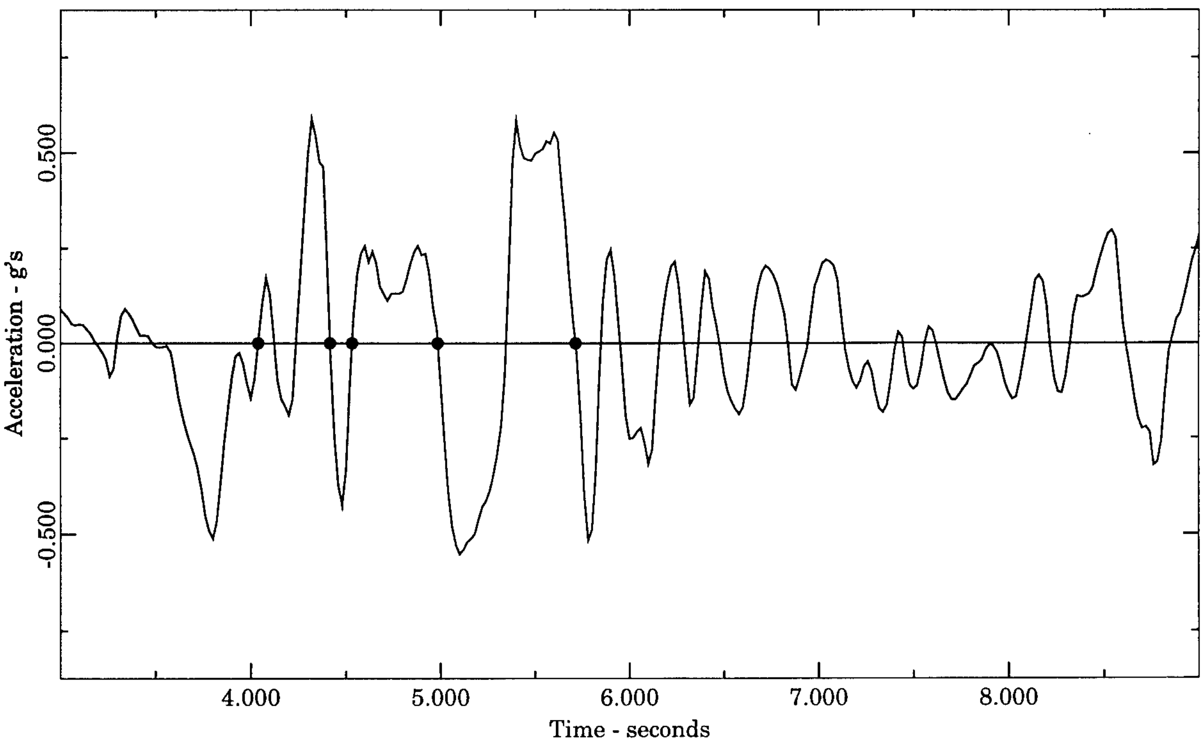
One of the reasons previously advanced (Defense Nuclear Agency, 1994) as to why ground motions from explosions do not adequately simulate earthquake motions is that explosion-generated motions have very much shorter durations. In this context, we compared response spectra computed from short segments of earthquake records to the response spectra computed from the complete records. Some examples of these comparisons follow.

A Northridge Earthquake record from the Newhall fire station parking lot is shown in Figure 3-19. The complete record is shown in the Figure 3-19a , and the large-amplitude part of the record is shown to a larger scale in Figure 3-19b. Several spectra computed from portions of this record are shown in Figure 3-20; the dashed line is the spectrum computed from the complete record. As indicated by the legend, the other spectral traces are for one-half cycle, one cycle, etc. One-half cycle is defined as the portion of the acceleration record between two adjacent crossings of the time axis. The end of the first half cycle is chosen as the first crossing after the first large-amplitude excursion and is shown in Figure 3-19b by the first (left-most) black dot. The other four black dots indicate the ends of the other four record segments for which spectra are plotted in Figure 3-20. This scheme is also used in the subsequent pairs of plots discussed below.

Spectra for the first three segments shown in Figure 3-20 are not particularly good approximations to the complete-record spectrum. However, the 3-cycle plot is a very good approximation. Note that the peak acceleration occurs during the third cycle.



a. Full record.



b. Partial record.

Figure 3-19. Northridge record on soil (Newhall fire station).

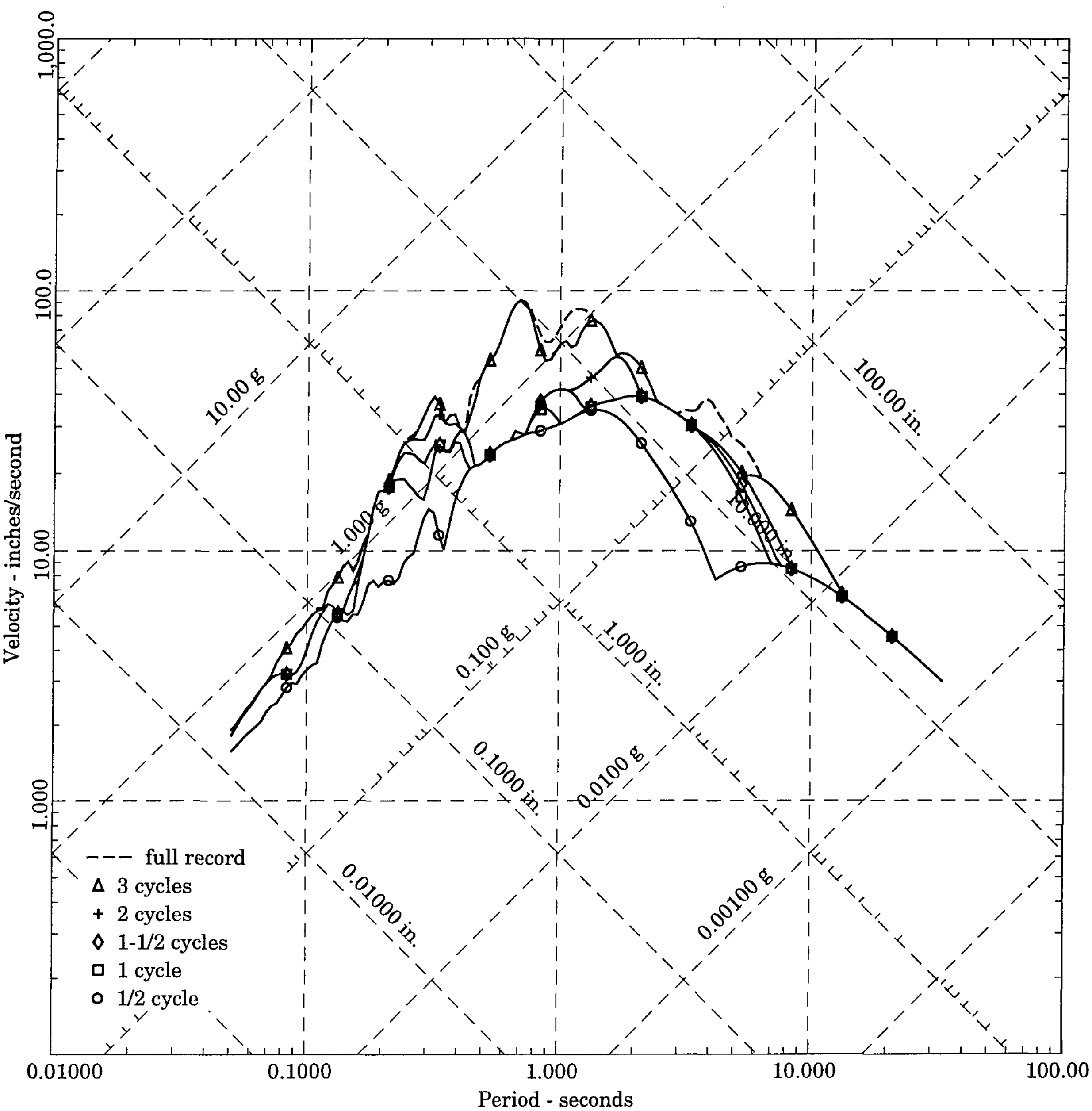


Figure 3-20. Spectra from the record of Figure 3-19.

A Northridge Earthquake record from the Sylmar hospital parking lot is shown in Figure 3-21, and the corresponding spectral plots are shown in Figure 3-22. The first record-segment spectrum that encompasses the peak acceleration is the 2-cycle plot. Except in the period range from about 1.2 to 2 seconds, it is a very good approximation to the complete-record spectrum. The 3-cycle plot is a slightly better approximation. Both of the records shown in Figures 3-19 and 3-21 were made by accelerometers founded on soil.

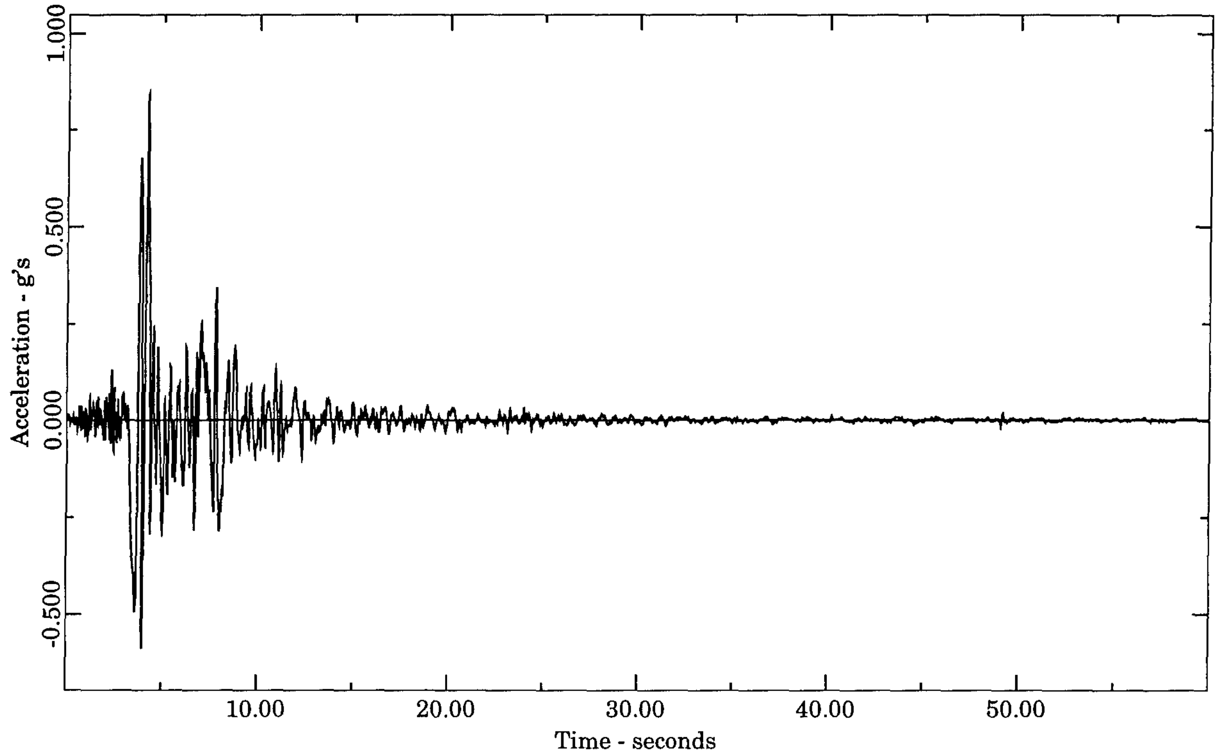
Two "on-rock" records (made by accelerometers founded on rock) and their associated spectral plots are shown in Figures 3-23 through 3-26. In each case, the first full cycle includes the peak acceleration, and the one-cycle spectrum is a good approximation to the complete-record spectrum.

As an example of on-structure motions, a Northridge Earthquake record from the left abutment of the Pacoima dam is shown in Figure 3-27, and associated spectral plots are shown in Figure 3-28. The peak acceleration occurs during the second cycle, and the 2-cycle spectrum is a very good approximation to the complete-record spectrum.

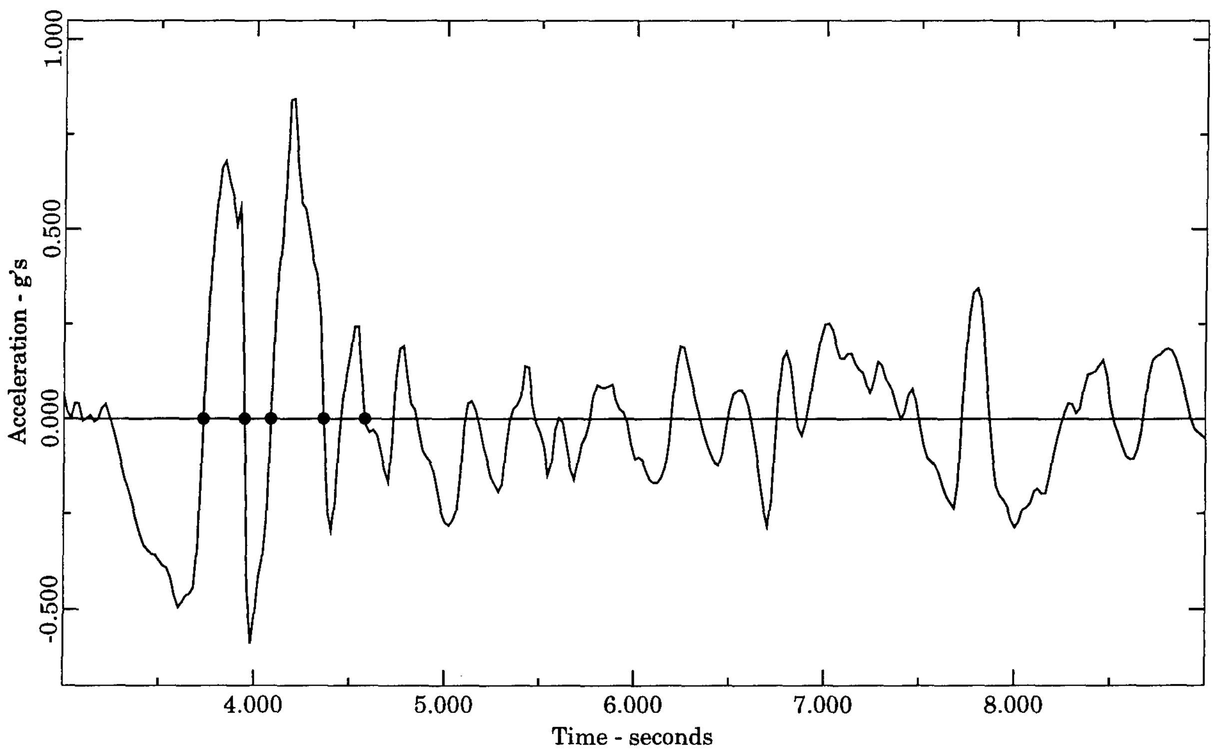
The above examples certainly do not constitute a rigorous proof that the duration of the record is unimportant. However, they do indicate that, at least as represented by response spectra, the duration of the ground motion has little effect on response as long as the peak acceleration is included in the portion of the record from which the spectrum is computed. This implies that "short duration" is not a valid reason for rejecting the use of explosion-generated ground motions to simulate earthquake motions. This, of course, does not address other potential reasons such as (1) more large-amplitude stress reversals caused by earthquake motions, (2) the approximately one-decade difference in the period at which peak spectral velocity occurs, and (3) the fact that earthquake ground motions are usually predominantly shear waves, while the explosion-generated motions are predominantly dilatational waves.

3.9 PRELIMINARY OBSERVATIONS.

The following observations are based on the preliminary work discussed in Sections 3.1 through 3.8:



a. Full record.



b. Partial record.

Figure 3-21. Northridge record on soil (Sylmar hospital).

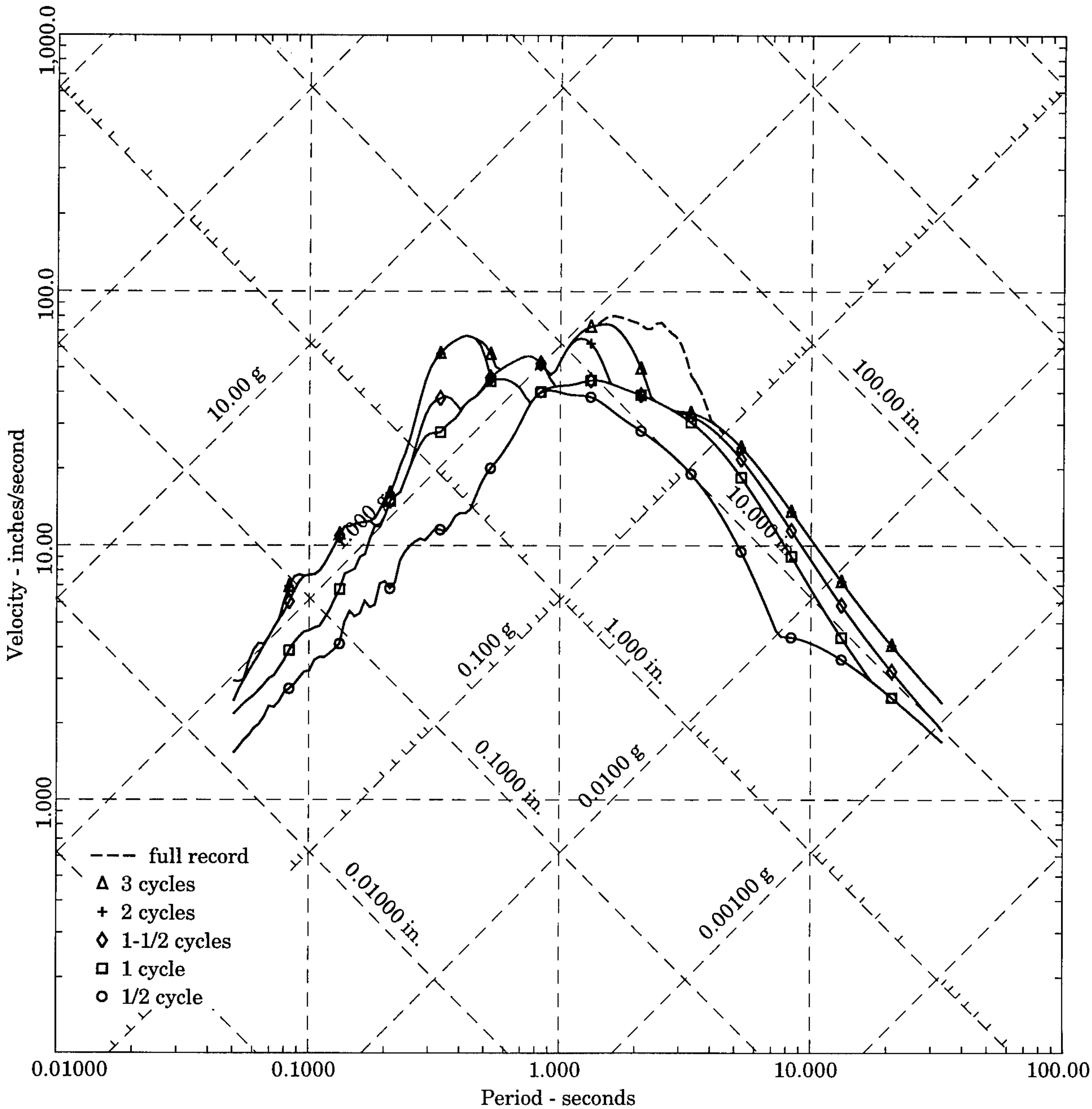
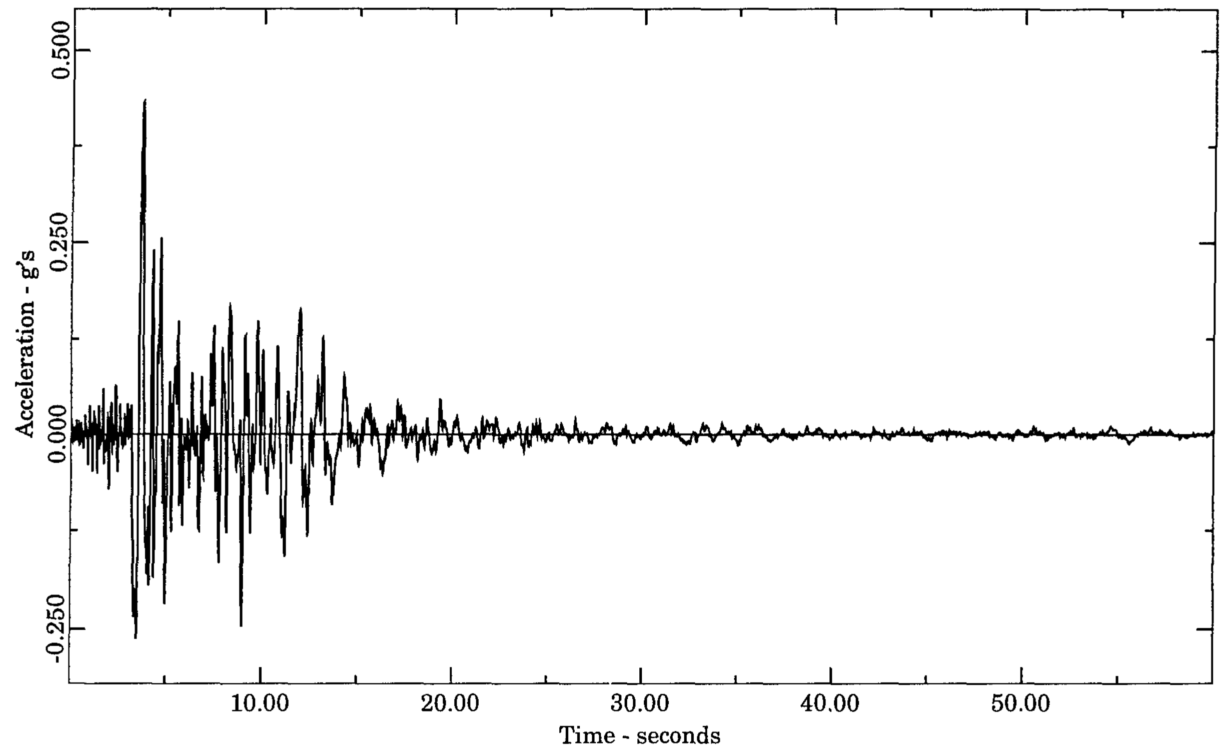
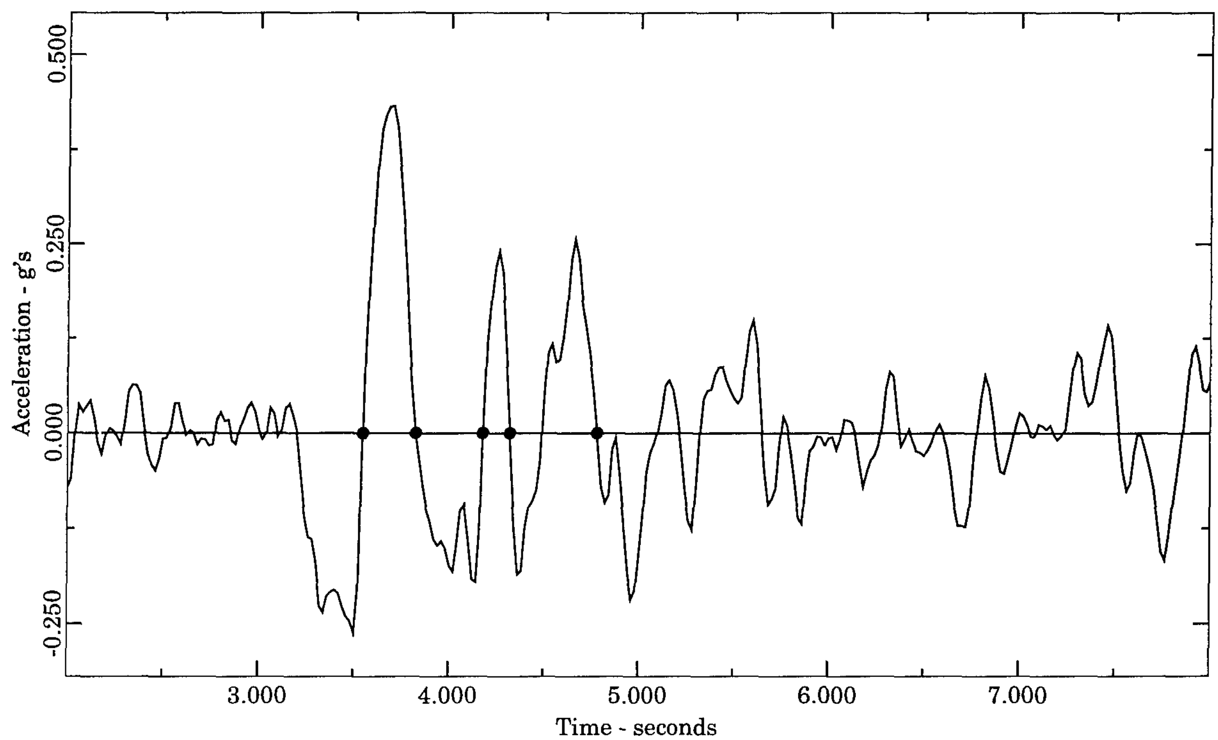


Figure 3-22. Spectra from record of Figure 3-21.



a. Full record.



b. Partial record.

Figure 3-23. Northridge record on rock (Pacoima dam - Kagel Canyon).

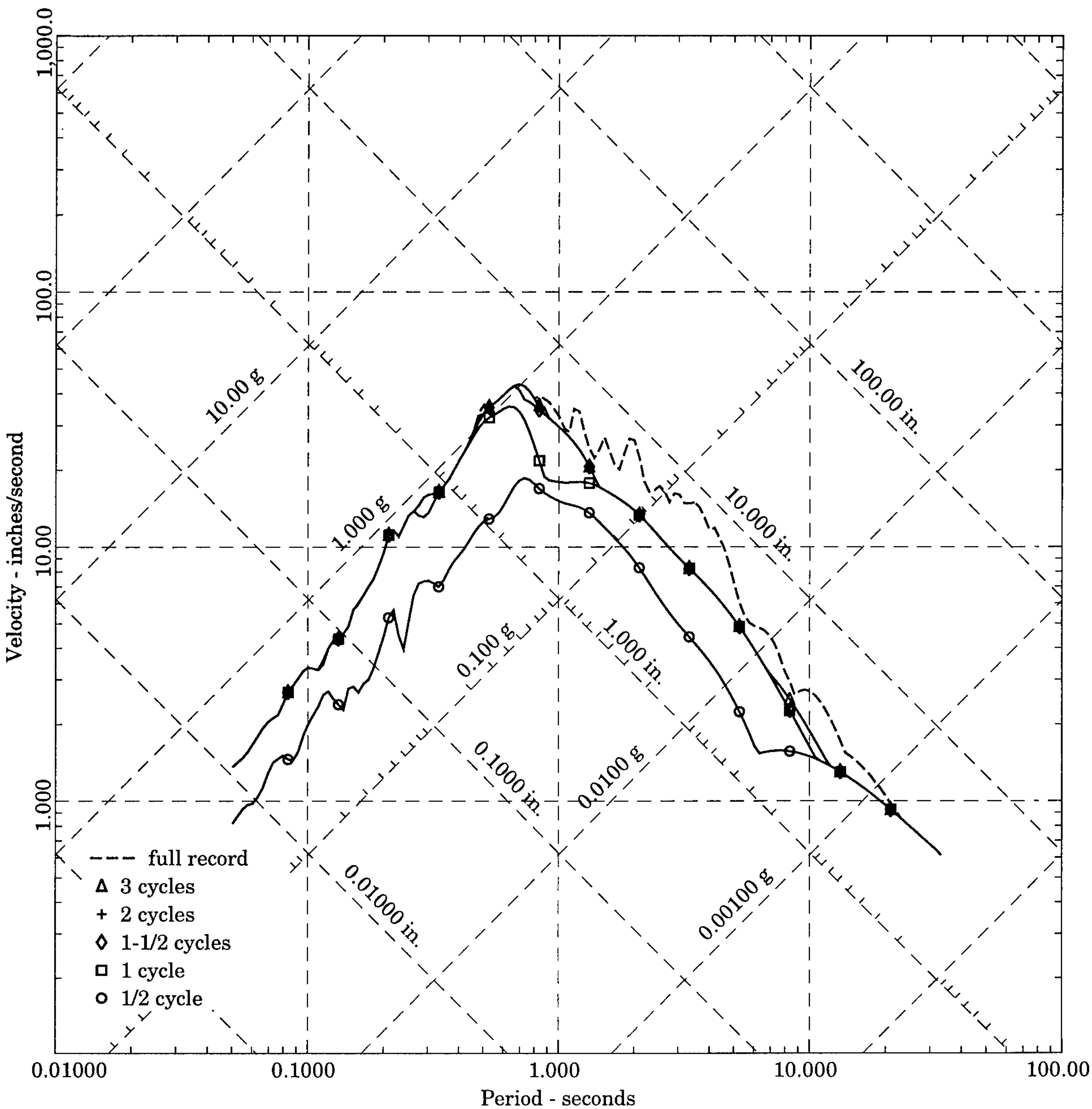
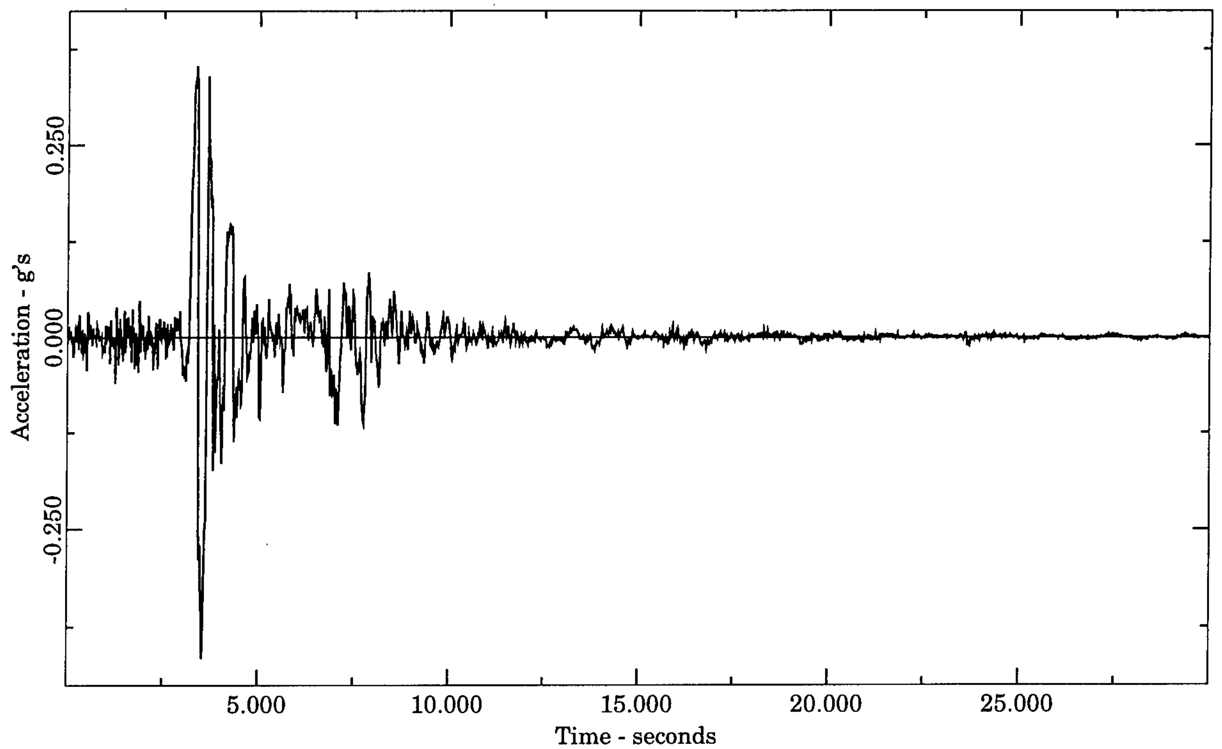
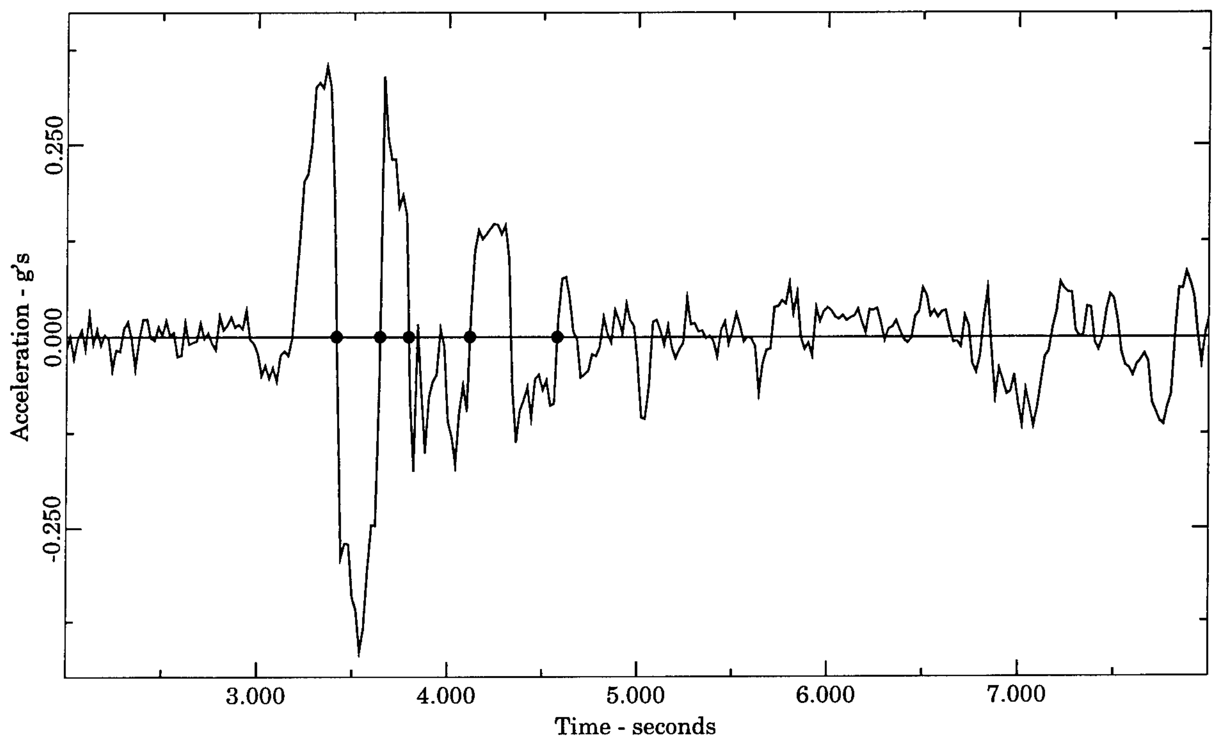


Figure 3-24. Spectra from record of Figure 3-23.



a. Full record.



b. Partial record.

Figure 3-25. Northridge record on rock (Paicoma dam - downstream).

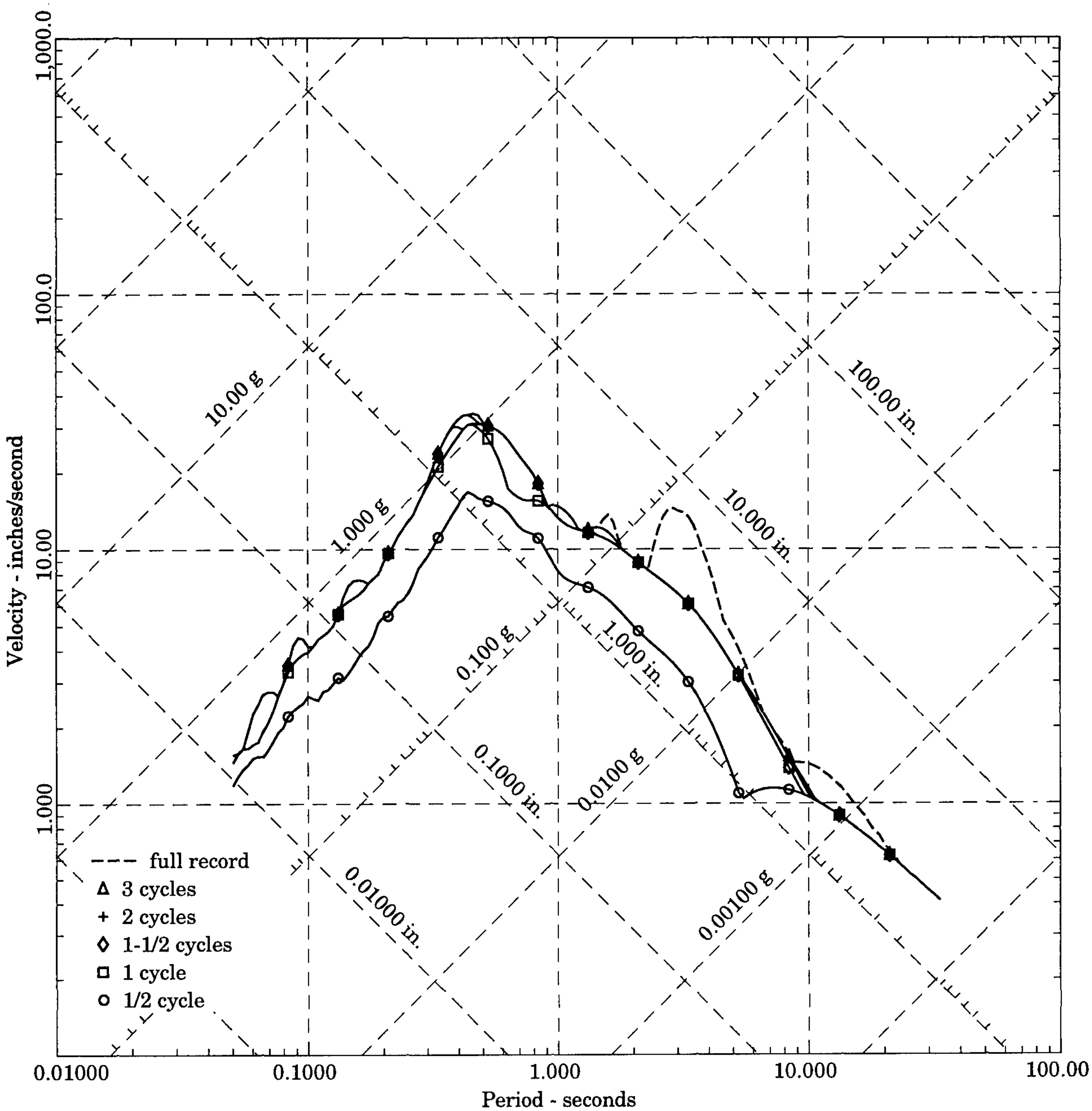
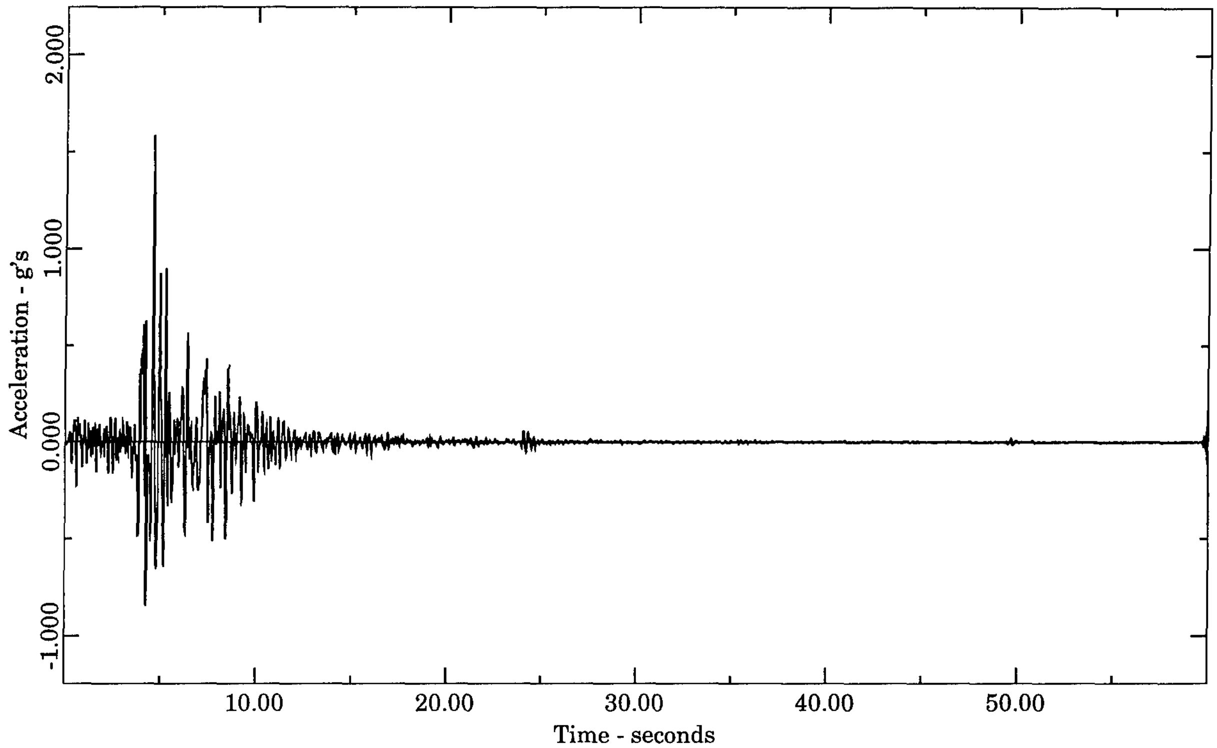
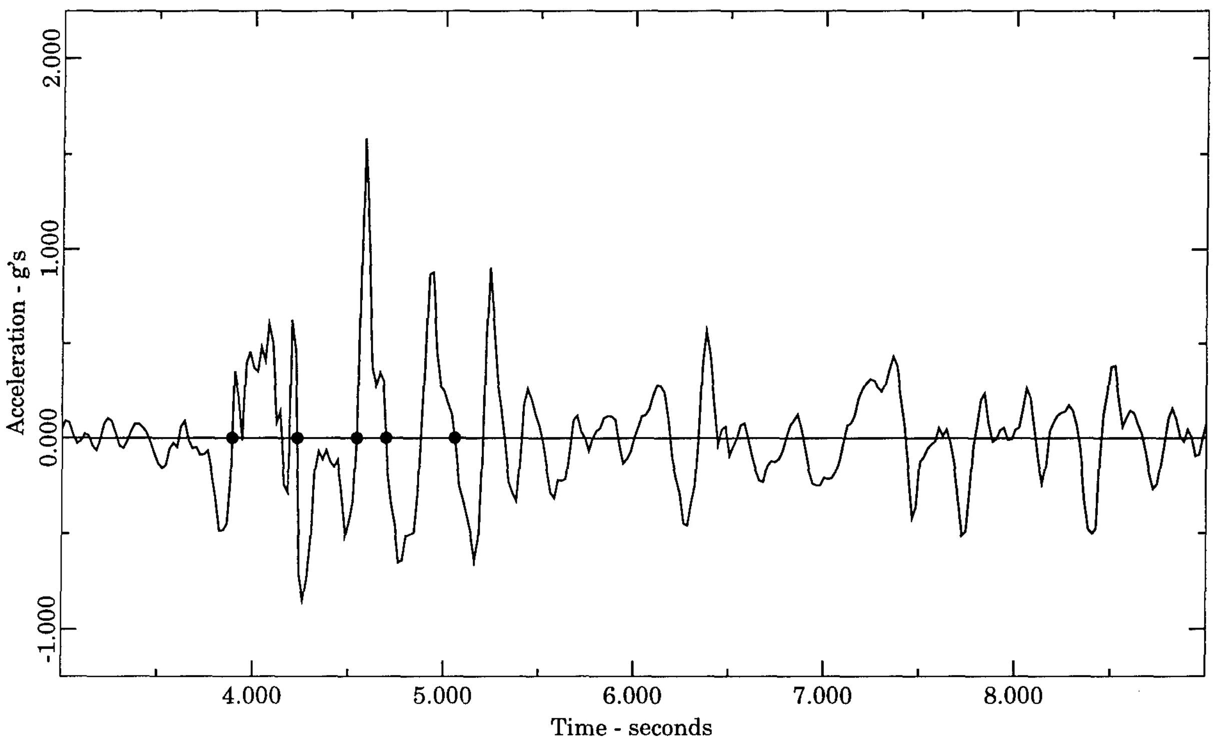


Figure 3-26. Spectra from record of Figure 3-25.



a. Full record



b. Partial record

Figure 3-27. Northridge record on a structure (Pacoima dam - left abutment).

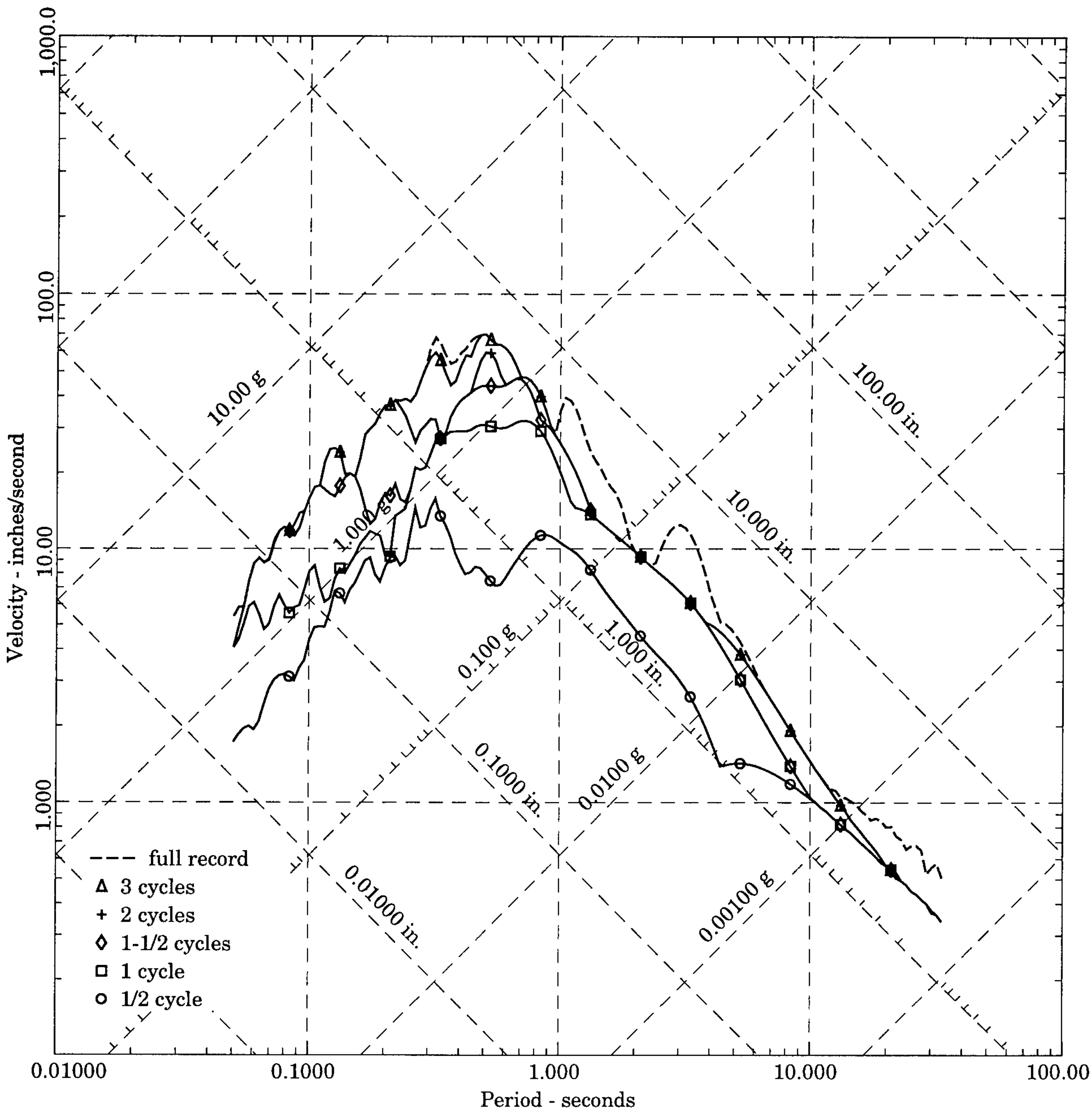


Figure 3-28. Spectra from record of Figure 3-27.

- Peak spectral velocities for the UGT spectra range from about 30 inches per second (Figure 3-12) to a little more than 200 inches per second (Figure 3-7).

- Earthquake spectral velocities peak at periods of about one second or more.

- UGT spectral velocities (at least for values up to about 200 inches per second) peak at periods on the order of 0.1 to 0.3 second.

- All of the earthquake spectra (including predicted and "measured" spectra) have similar shapes.

- The UGT spectra are a bit broader than the earthquake spectra but are quite similar in shape to one another.

- As a consequence of the approximately one decade separation in the peak spectral velocities (second and third observations above), the peak spectral accelerations for earthquakes are about an order of magnitude lower than those for UGTs when the peak spectral velocities are comparable.

  Peak earthquake spectral displacements are somewhat higher then the corresponding peak UGT spectral displacements, although the relationship does not appear to be as consistent as it is for peak spectral accelerations.

- As discussed in Section 2, tunnel behavior is likely to be sensitive to particle velocity, which indicates that tunnel damage from UGTs may be related to the ground motion environment as reflected by spectral velocities. We have demonstrated that it is not difficult to find earthquake spectra that compare favorably with the UGT spectra on the basis of spectral velocity.

- The discussion in Section 3.8 indicates that "short duration" is not a valid reason for rejecting the use of explosion-generated ground motions to simulate earthquake motions.

SECTION 4

TUNNEL RESPONSE

Available postshot data were reviewed for five events (the four events from which the response spectra discussed in Section 3 were derived plus one other event of comparable size). These data were evaluated to determine the maximum range at which significant tunnel damage occurred. The spectrum from a UGT record at this range was then compared with appropriate earthquake spectra. These efforts are discussed in this section.

4.1 DAMAGE ASSESSMENTS.

Damage assessments for five events were made by reviewing two sources of data. One of these was a Raytheon Services Nevada report (Schulenburg, 1995) that included photographs of tunnel damage and summarized some of the reentry reports prepared by others. The second source was a package of materials provided by DNA (Harris-West, 1995), which included excerpts from several reports containing reentry observations that pertain to tunnel damage. Facts gleaned from the above documents that relate to the limiting range at which significant tunnel damage occurred are summarized by event as follows:

Event 5

- No significant tunnel damage was observed beyond the end of stemming (EOS) @ RS 510 feet (510 feet from the working point)

Event 6

- Invert broken at EOS @ RS 510 feet
- Fractures in the invert @ RS 568 feet, but these coincided with fractures mapped pretest

Event 13

- Heavily damaged alcove in LOS drift @ RS 315 feet
- Spall up to 2 feet thick @ RS 396 feet (associated with fault planes)

- Considerable floor heave in bypass drift between RS 279 and 315 feet
- No significant damage beyond RS 396 feet

<u>Event 25</u>

- Invert of LOS drift buckled just beyond EOS @ RS 604 feet
- Back collapsed in crosscut @ RS 659 feet (side-on loading) - about 50 feet from the limit of the shock conditioning zone identified by a pretest seismic survey
- Only minor damage occurred in the LOS and bypass drifts between the crosscut @ RS 659 feet and EOS @ RS 604 feet

<u>Event 29</u>

- Major spalling between RS 505 and 660 feet in bypass drift
- Alcove pillar collapsed @ RS 530 feet
- Moderate spalling in LOS drift between RS 505 and 643 feet
- Major spalling in bypass and crosscut drifts between RS 725 and 800 feet - associated with a fault zone mapped pretest

4.2 ESTIMATED DAMAGE THRESHOLD.

In the five events for which damage is described above, the limit of significant tunnel damage appears to occur at a range of approximately 660 feet (approximately 200 meters). In making this estimate the damage between RS 725 and 800 feet in Event 29 was ignored because it was associated with a fault zone mapped pretest.

4.3 COMPARISON OF UGT AND EARTHQUAKE SPECTRA.

Among the UGT data from Event 25 is a record from a free-field measurement location whose range (200 meters) coincides almost exactly with the 660-foot damage-threshold range estimated as described above. This is the "200m" measurement location. The response spectrum from the radial measurement at this location was compared with selected earthquake response spectra as discussed in the following subsections.

4.3.1 Earthquake Measurements on Rock.

Most of the earthquake records that were evaluated during this program were made with accelerometers founded on soil or located in (or on) structures. There are some records from the January 17, 1994 Northridge Earthquake that were made with the accelerometers founded on rock at two locations, both near the Pacoima dam. These records were shown in Figures 3-23 and 3-25. Response spectra from the largest components measured at the "on-rock" locations are plotted with the spectrum from the Event 25, 200-meter measurement in Figure 4-1. Peak spectral velocities and accelerations from the earthquake records are well below those from the UGT record. However, the peak spectral displacements from the earthquake records are slightly higher than those from the UGT record. Also, the earthquake spectral velocities peak at somewhat higher periods than does the UGT spectral velocity, although there is not as much difference as in most of the on-structure spectra considered during the preliminary work reported in Section 3.

4.3.2 Earthquake Measurements on Soil.

We also compared the Event 25, 200-meter spectrum with spectra from two of the Northridge Earthquake records made with accelerometers founded on soil, one from the Newhall fire station and the other from the Sylmar hospital parking lot. These records were shown in Figures 3-19 and 3-21, respectively. They had two of the highest ground-motion spectral velocities produced by the Northridge Earthquake. These spectra are plotted with the spectrum from the Event 25, 200-meter measurement in Figure 4-2. Peak spectral velocities from all three records are approximately equal. Peak spectral accelerations from the earthquake records are about an order of magnitude lower than those from the UGT record, and peak spectral displacements are about an order of magnitude higher. Also, the earthquake spectral velocities again peak at significantly higher periods than does the UGT spectral velocity.

It is generally accepted in the earthquake engineering community that earthquake ground motions and their spectra decrease with depth (or more correctly, are magnified as they approach the surface). Considerable research is currently under way to quantify these site-dependent effects. These research programs use the results of accelerometer measurements made at various depths in deep (hundreds of feet) boreholes. One such effort, reported by Archuleta and others (Archuleta, 1992),

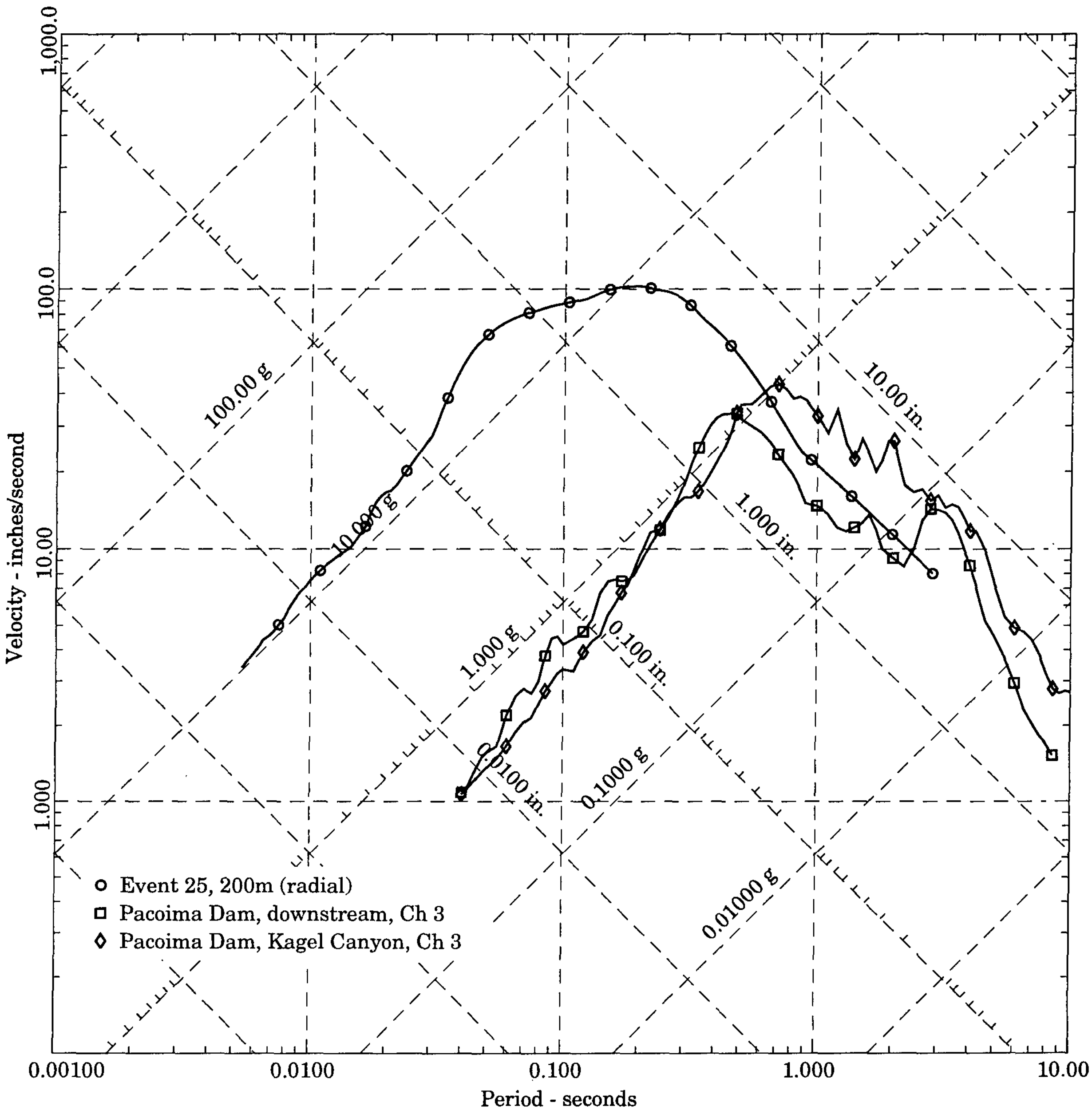


Figure 4-1. Event 25, 200 meter spectrum compared with Northridge Pacoima Dam Earthquake spectra.

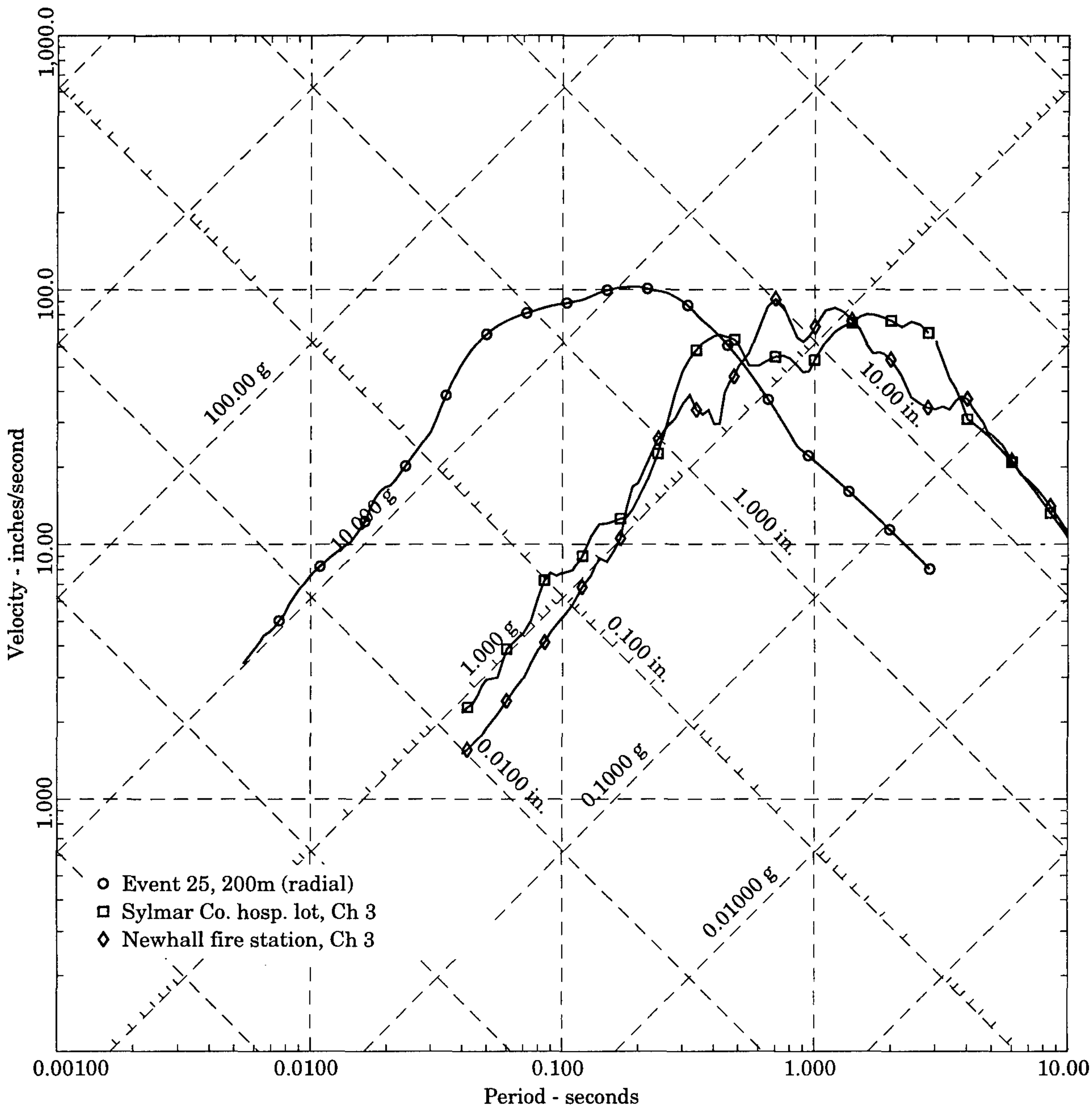


Figure 4-2. Event 25, 200 meter spectrum compared with Northridge, Sylmar hospital lot and Newhall fire station earthquake spectra.

studied the results of measurements made by a downhole array of accelerometers during 280 small earthquakes (magnitudes ranging from 1.2 to 4.7) between July 1989 and July 1991. The downhole array is located approximately 7 kilometers from the San Jacinto fault in Garner Valley southeast of Riverside, California. The soil profile consists of approximately 20 meters of soil, underlain by approximately 30 meters of weathered granite, which is underlain by the granite bedrock. Accelerometers are located at depths zero, 6, 15, 22, and 220 meters.

Archuleta reported that response spectra from records at the 22-meter level (a small distance below the bottom of the soil layer) are generally lower than spectra from records made at the surface by about a factor of three. We scaled down the earthquake surface spectra shown in Figure 4-2 by a factor of three in order to approximate the spectrum for a tunnel near the top of a rock stratum that is overlain by about 20 meters of soil. These scaled spectra are plotted with the Event 25, 200-meter spectrum in Figure 4-3. The scaled peak spectral accelerations and velocities from the earthquake records are well below those from the UGT record. However, the scaled earthquake spectral displacements are higher than the UGT spectral displacement by a factor of about two.

4.3.3 Predicted Earthquake Spectra for Rock.

One further spectral comparison was made using predicted earthquake ground-motion response spectra. Response spectra predictions were made using the Boore, Joyner, and Fumal prediction method discussed in Section 3.4. One of the primary variables in the prediction method is the shear wave propagation velocity of the medium in which the earthquake motions propagate. Event 25 was conducted in the P-Tunnel complex at the Nevada Test Site. In an attempt to make the predictions applicable to P-Tunnel tuff, we used the "pre-event average" shear wave seismic velocity of 1390 meters per second reported for a seismic survey in the P-Tunnel complex by Hopkins and Baldwin (Hopkins, 1992).

Predictions were made for a magnitude 7.7 earthquake (the largest magnitude for which the prediction method is applicable) at a range of 5 kilometers and for a magnitude 7.0 earthquake at a range of 0.5 kilometer. These two predicted spectra are plotted with the Event 25, 200-meter spectrum in Figure 4-4. This comparison is quite similar to the comparison with scaled surface motion spectra.

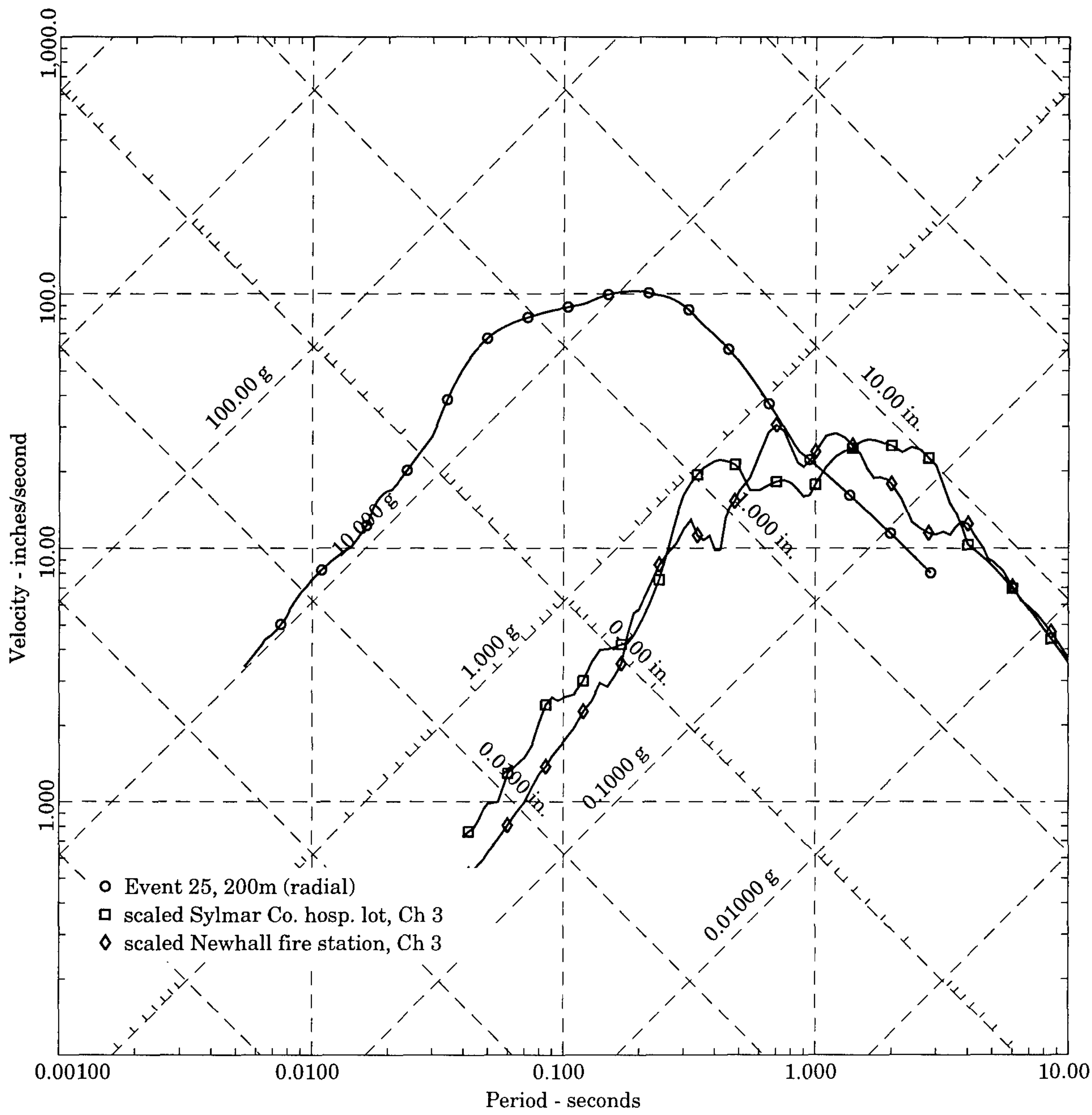


Figure 4-3. Event 25, 200 meter spectrum compared with scaled Northridge, Sylmar hospital lot and Newhall fire station earthquake spectra.

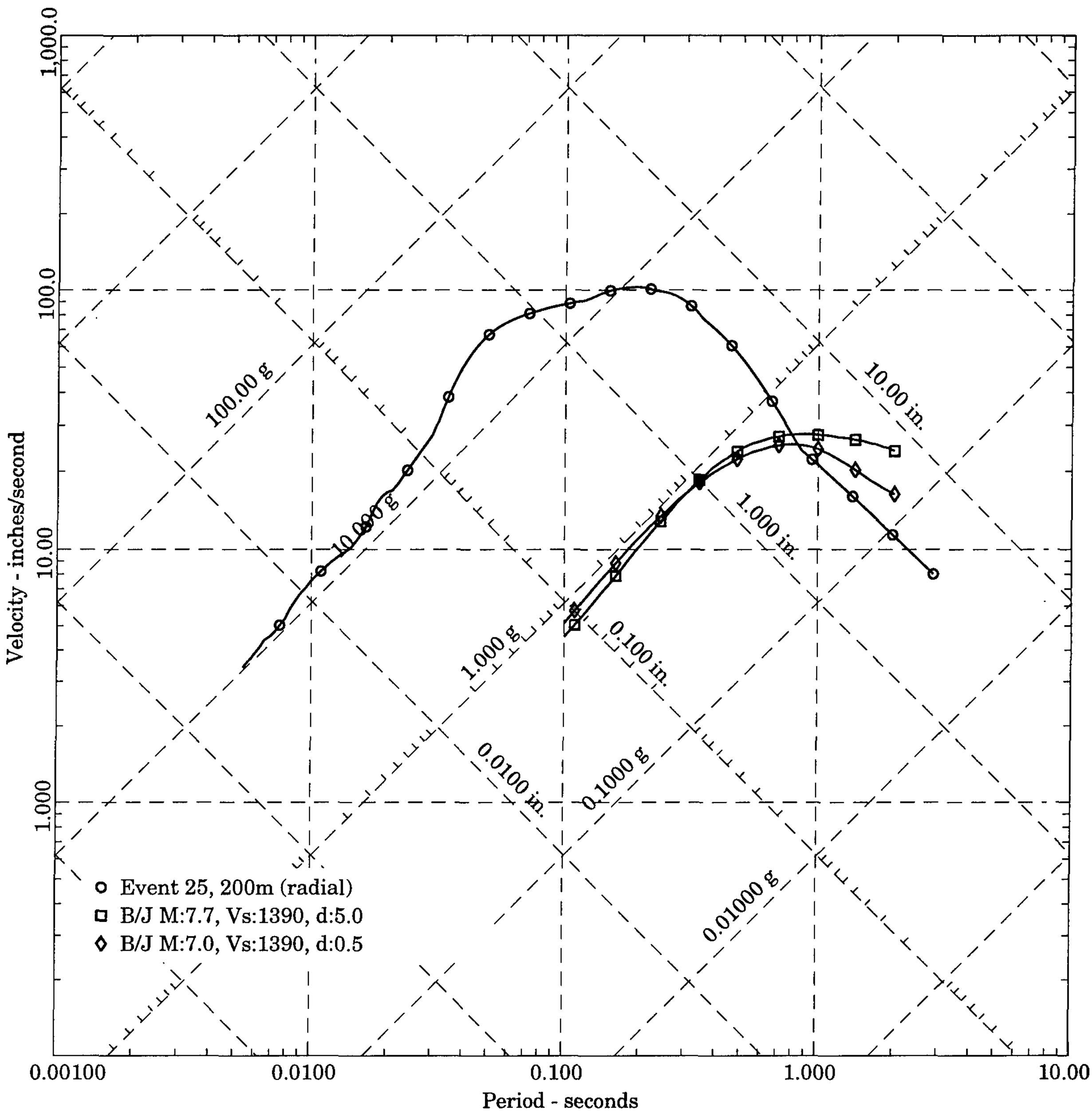


Figure 4-4. Event 25, 200 meter spectrum compared with Boore & Joyner predictions.

4.4 OBSERVATIONS.

At the beginning of this program (see Section 2), we concluded that tunnel behavior is likely to be sensitive to particle velocity, which indicates that tunnel damage from UGTs may be related to the ground motion environment as reflected by spectral velocities. We have demonstrated (as reported in Section 3) that it is not difficult to find earthquake spectra that compare favorably with the UGT spectra on the basis of spectral velocity. At the end of the preliminary work, we hypothesized that it might be possible to demonstrate, through the use of UGT data, that there is little likelihood of damage to tunnels at depth from earthquake-induced ground shaking. If this were possible, it would add quantitative evidence in support of the anecdotal data reported by Sharma and Judd (Sharma, 1991) and others.

The discussions in Sections 4.1 through 4.3 indicate that one can probably make a good case that the spectral velocities and accelerations caused by earthquakes at typical depths for tunnels in rock will be significantly less than those associated with the tunnel-damage threshold for the UGT events we have considered. However, the same case cannot be made for spectral displacements. At least two significant questions remain to be answered:

- Does the response spectrum accurately reflect the behavior of a tunnel?
- If so, is spectral displacement less important than either spectral velocity or acceleration?

Unfortunately, the available UGT data are probably insufficient to answer either of these questions empirically. Considerable insight could be gained through an extensive analytical program in which both ground motions and tunnel response are simulated parametrically. Recommendations on this subject are presented in Section 5.

SECTION 5

RECOMMENDATIONS

As originally envisioned, Phase II of this program would have proceeded with documenting the ground shock data from additional Underground Nuclear Tests (UGTs) and correlating these data with (1) the response of underground facilities (adits, alcoves, etc.) at the Nevada Test Site and (2) earthquake ground motions. We have concluded that such an effort is probably not appropriate. This conclusion is based primarily on the recognition that there were only a relatively small number of events (in addition to those considered during Phase I) in which free-field acceleration measurements were made at ranges that are believed to be large enough* to yield spectral velocities of interest to the earthquake engineering community (on the order of 200 inches per second or less).

Observations made during the Phase I effort have led us to conclude, however, that there are some things that should be done because of their potential usefulness to the earthquake engineering community. These recommended efforts are outlined in the following two subsections. A third recommendation that resulted only indirectly from the investigation reported herein is presented in Section 5.3.

5.1 EARTHQUAKE DATA EVALUATION.

The National Center for Earthquake Engineering Research recently sponsored a study of tunnel damage caused by earthquakes (Power, 1995). The data contained in Power's report should be evaluated to determine the correlation between damage levels and ground motion levels as reflected by response spectra. This would allow correlations of damage estimates from UGT experience with empirical earthquake data.

5.2 ANALYTICAL PROGRAM.

An analytical program should be conducted to relate ground motion response spectra to the response of tunnels in tuff. This program would employ dynamic finite element

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* We recently learned that underground free-field acceleration measurements were made at large ranges by Los Alamos National Laboratory (ESS-3) on several DNA events. Some of the ranges were large enough that the peak accelerations recorded were less than one g.

calculations to simulate the ground motions and estimate the resulting tunnel strains. The response of tunnels to comparable earthquake and UGT ground motions would be investigated parametrically. Some of the important questions that would be addressed by this analytical investigation are as follows:

- What part of the ground motion spectrum is most directly related to tunnel response?
- What are the differences in tunnel response caused by dilatational wave (UGTs) and shear wave (earthquakes) motions?
- What is the threshold magnitude of peak ground motions (as measured by spectral accelerations, velocities, and displacements) that produces tunnel strains consistent with significant tunnel damage?
- Is it possible to develop an equivalent earthquake tunnel damage spectrum from the UGT data base?

5.3 SEISMOLOGICAL INVESTIGATION.

An investigation should be conducted by a qualified seismologist to identify (1) the wave composition and orientation of selected UGT records and (2) their potential usefulness for resolving ground motion prediction issues that are important to the earthquake engineering community. Two examples of the work envisioned are as follows:

- Characterize UGT ground motions (particularly surface motions) and compare them with earthquake motions at appropriate ranges.
- Analyze UGT records to gain insight into the composition of UGT waves and how it compares with earthquake wave composition.

5.4 CONCLUDING REMARKS.

As stated above, we concluded that Phase II of this technology transfer study is probably not appropriate. However, we believe that if the forgoing recommendations are accepted, the results should definitely be useful and of interest to the earthquake engineering community.

SECTION 6

REFERENCES

Archuleta, R. J., et al, "Garner Valley Downhole Array of Accelerometers: Instrumentation and Preliminary Data Analysis," Bulletin of the Seismological Society of America, Vol. 82, No. 4, pp. 1592-1621, August 1992.

Blume, John A., et al, *Design of Multistory Reinforced Concrete Buildings for Earthquake Motions*, Portland Cement Association, 33 West Grand Avenue, Chicago, IL, 1961.

Boore, D. M., et al, "Estimation of Response Spectra and Peak Accelerations from Western North American Earthquakes: An Interim Report," U. S. Geological Survey Open-File Report 93-509, 1993.

Boore, D. M., et al, "Estimation of Response Spectra and Peak Accelerations from Western North American Earthquakes: An Interim Report, Part 2," U. S. Geological Survey Open-File Report 94-127, 1994.

Defense Nuclear Agency, Minutes of the Ground Shock Technology Transfer Working Group Meeting held in Albuquerque, NM on 25-26 April 1994.

Harris-West, Barbara, DNA, private communication to D. N. Burgess, BDM Engineering Services Company, 11 July 1995.

Hopkins, S. P. and M. J. Baldwin, "Observations in the u12P.04 Drifts of Probable Shock Effects from the MISSION CYBER and DISKO ELM Events," GEO-1394, Raytheon Services Nevada, 18 August 1992.

Idriss, I. M. and J. I. Sun, "Users Manual for SHAKE91, A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits, Program Modified based on the Original SHAKE program published in December 1972 by Schnable, Lysmer & Seed," Center for Geotechnical Modeling,

Department of Civil & Environmental Engineering, University of California, Davis, California, 1992.

Newmark, N. M., "Problems in Wave Propagation in Soil and Rock," International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, 1968.

Nigam, N. V. and P. C. Jennings, "Calculation of Response Spectra from Strong-Motion Earthquake Records," *Bulletin of the Seismological Society*, Vol. 59, No. 2, pp. 909-922, April 1969.

Paz, Mario, *Structural Dynamics. Theory and Computation*, 3rd ed, Van Nostrand Reinhold, New York, 1991.
Schulenburg, K. L., "Technology Transfer. Ground Shock Damage Report," Raytheon Services Nevada, September 1995.

Power, M., et al, "Empirical Data Compilation and Correlations on the Seismic Performance of Tunnels," Geomatrix Consultants, 1995.

Schulenburg, K. L., "Technology Transfer. Ground Shock Damage Report," Raytheon Services Nevada, September 1995.

Sharma, S. and W. R. Judd, "Underground Opening Damage from Earthquakes," *Engineering Geology*, Elsevier Publishers B. V., Amsterdam, 30(1991) 263-276.
Silva, W. J., "State-of-the-Art for Assessing Earthquake Hazards in the United States, WES Rascal Code for Synthesizing Earthquake Ground Motions," U. S. Army Corps of Engineers report, 1987.

St. John, C. M. and T. F. Zahrah, "Aseismic Design of Underground Structures," R-8411-5616, prepared for the National Science Foundation, Agbabian Associates, June 1985.

Wang, J-N, "Seismic Design of Tunnels. A Simple State-of-the-Art Design Approach," Parsons Brinckerhoff Quade & Douglas, June 1993.

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